TIME-DRIVEN LIFE CYCLE COST ESTIMATION SYSTEM FOR PRODUCT FAMILY DESIGN

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Abstract

The growing implementation of a product family design has led to the need for a product family design support system. This would estimate the life cycle cost of each component level of various structures of different product families at the early stage of product development. Various systems have been proposed in the literature to estimate the life cycle cost of a product family. However, the existing systems do not provide satisfying answers to several problems. First, the existing cost estimation systems have their own difficulties in fulfilling the requirement to estimate the life cycle cost of each component level of a product family for design purposes, in different types and sizes of companies that use different technologies and approaches. Second, in order to estimate the end of life cost, none of the existing cost estimation systems determine the end of life strategy of a product family on the sub module level. Third, the existing cost estimation systems are not able to, or experience difficulties in, estimating the cost of different structures of different product families. Finally, how to use the available attributes to estimate the life cycle cost at the early stage of product development has not yet been studied.

The aim of this research is to develop a product family design support system, which is able to estimate the life cycle cost of each component level of different product families at the early stage of product development.

To achieve its aim, this research implements an adapted time-driven activity-based costing technique to develop a life cycle cost model for the design purpose. The life cycle cost model can be used to allocate and calculate the cost of each component level of a product family and can be adapted for different technologies and approaches with less effort and time. Then, a method is developed in this research to determine the end of life strategy of a product family on the sub module level. The end of life strategy is integrated with the life cycle cost model to estimate the end of life cost of a product family. Next, this research proposes a method that estimates the cost of different structures of different product families based on the modular product architecture approach. The implementation of this method can reduce the required time and effort for updating process in estimating the life cycle cost for different structures of different product families. Finally, a knowledge-based

system is developed in this research to transform the available information into what is required to estimate the life cycle cost and evaluate the design of a product family at the early stage of product development.

This research contributes in the design research area by providing a new design support system that can help a designer in estimating the life cycle cost of each component level of different product families at the early stage of product development. By implementing the developed cost estimation system, the manufacturing company will be able to evaluate various product family designs at the early stage of product development, adjust the product family cost as early as possible before a significant cost is incurred, and reduce the product family cost without resulting in many difficulties caused by late modification. In addition, the manufacturing company can evaluate the impact of the end of life regulation to the end of life cost and analyse the cost and the benefit in conducting the remanufacturing and refurbishing processes at the early stage of product development. The outcome is that the manufacturing company is able to develop various cost effective product families in a shorter lead-time and minimise the impact of the developed product family to the environment.

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List of Abbreviations

%RM	Percentage of the Recovered Material Usage
%RS	Percentage of the Recovered Sub Module Usage
A%	% Taken Back Product of Production Volume
AR	Assembly Repetition
B%	% Working Product of Taken Back Product
C%	% Working Sub Assembly of Non-Working Product
ICAC	In-house Component Activity Cost
D	Diameter
D%	% Tear/Wear Sub Assembly of Working Sub Assembly
E%	% Repairable Sub Assembly of Non-Working Sub Assembly
F%	% Repairable Permanent Joined Sub Assembly
G%	% Reconditionable Tear/Wear Sub Assembly
H	Height
H%	% Working Part of Taken Back Product
I%	% Tear/Wear Part of Working Part
J%	% Repairable Part of Non-Working Part
JPVPP	Joining Production Volume of Product Platform
JPVPV	Joining Production Volume of Product Variant
K%	% Repairable Permanent Joined Part
L	Length
L%	% Recondition able Tear/Wear Part
MBO	Material Batch Order
MC	Raw Material Cost
MU	Raw Material Usage
OCAC	Outsourced Component Activity Cost
OCBO	Outsourced Component Batch Order
OCC	Outsourced Component Cost
PC	Production Capacity
PPAC	Product Platform Activity Cost
PV	Production Volume of Product Variant
PVAC	Product Variant Activity Cost
PVAPV	Production Volume for All Product Variants
PVIC	Production Volume of In-house Component
QAD	Quantity Activity Driver
QC	Quantity of Components
QCRM	Quantity of Components for Recovered Material
QM	Quantity of Modules
QNICP	Quantity of Non-Permanently Assembled In-house Parts for Reconditioned
QNICS	Quantity of Non-Permanently Assembled In-house Sub Assemblies for Reconditioned
QNILS	Quantity of Non-Permanently Assembled In-house Sub Assemblies for Replaced
QNIMP	Quantity of Non-Permanently Assembled In-house Parts for Recovered Material
QNIMS	Quantity of Non-Permanently Assembled In-house Sub

	Assemblies for Recovered Material
QNIMSC	Quantity of Non-Permanently Assembled In-house Sub Assembly' Components for Recovered Material
QNIPP	Quantity of Non-Permanently Assembled In-house Parts for Repaired
QNIPS	Quantity of Non-Permanently Assembled In-house Sub Assemblies for Repaired
QNIRP	Quantity of Non-Permanently Assembled In-house Parts for Reused
QNIRS	Quantity of Non-Permanently Assembled In-house Sub Assemblies for Reused
QNOCP	Quantity of Non-Permanently Assembled Outsourced Parts for Reconditioned
QNOCS	Quantity of Non-Permanently Assembled Outsourced Sub Assemblies for Reconditioned
QNOLS	Quantity of Non-Permanently Assembled Outsourced Sub Assemblies for Replaced
QNOMP	Quantity of Non-Permanently Assembled Outsourced Parts for Recovered Material
QNOMS	Quantity of Non-Permanently Assembled Outsourced Sub Assemblies for Recovered Material
QNOMSC	Quantity of Non-Permanently Assembled Outsourced Sub Assembly' Components for Recovered Material
QNOPP	Quantity of Non-Permanently Assembled Outsourced Parts for Repaired
QNOPS	Quantity of Non-Permanently Assembled Outsourced Sub Assemblies for Repaired
QNORP	Quantity of Non-Permanently Assembled Outsourced Parts for Reused
QNORS	Quantity of Non-Permanently Assembled Outsourced Sub Assemblies for Reused
QOCO	Quantity of Outsourced Component Orders
QPICP	Quantity of Permanently Assembled In-house Parts for Reconditioned
QPICS	Quantity of Permanently Assembled In-house Sub Assemblies for Reconditioned
QPILS	Quantity of Permanently Assembled In-house Sub Assemblies for Replaced
QPIMP	Quantity of Permanently Assembled In-house Parts for Recovered Material
QPIMS	Quantity of Permanently Assembled In-house Sub Assemblies for Recovered Material
QPIMSC	Quantity of Permanently Assembled In-house Sub Assembly' Components for Recovered Material
QPIPP	Quantity of Permanently Assembled In-house Parts for Repaired
QPIPS	Quantity of Permanently Assembled In-house Sub Assemblies for Repaired
QPIRP	Quantity of Permanently Assembled In-house Parts for Reused
QPIRS	Quantity of Permanently Assembled In-house Sub Assemblies

	for Reused
QPMO	Quantity of Purchased Material Orders
QPO	Quantity of Product Orders
QPOCP	Quantity of Permanently Assembled Outsourced Parts for Reconditioned
QPOCS	Quantity of Permanently Assembled Outsourced Sub Assemblies for Reconditioned
QPOLS	Quantity of Permanently Assembled Outsourced Sub Assemblies for Replaced
QPOMP	Quantity of Permanently Assembled Outsourced Parts for Recovered Material
QPOMS	Quantity of Permanently Assembled Outsourced Sub Assemblies for Recovered Material
QPOMSC	Quantity of Permanently Assembled Outsourced Sub Assembly' Components for Recovered Material
QPOPP	Quantity of Permanently Assembled Outsourced Parts for Repaired
QPOPS	Quantity of Permanently Assembled Outsourced Sub Assemblies for Repaired
QPORP	Quantity of Permanently Assembled Outsourced Parts for Reused
QPORS	Quantity of Permanently Assembled Outsourced Sub Assemblies for Reused
QPR	Quantity of Production Runs
QRSM	Quantity of Recovered Sub Modules
QSM	Quantity of Sub Modules
QTBP	Quantity of Taken Back Products
ρ	Material Density
RCA	Resource Cost of Activity
RIC	Rate of In-house Component
RM	Rate of Raw Material
RMC	Recovered Material Cost
RMU	Recovered Material Usage
RMWC	Required Material Weight of Component
ROC	Rate of Outsourced Component
RPP	Rate of Product Platform
RPV	Rate of Product Variant
RR	Resource Rate
RRM	Rate of Recovered Material
RRS	Rate of Recovered Sub Module
RSC	Recovered Sub Module Cost
RSM	Rate of Sub Module
RSU	Recovered Sub Module Usage
RTA	Required Times to Perform Activity
SC	Storage Cost
SD	Storage Duration
SMC	Sub Module Cost
SMU	Sub Module Usage
SR	Storage Rate
SV	Storage Volume

TAC	Total Activity Cost
TBC	Taken Back Cost of Component
TBPAC	Taken Back Product Activity Cost
TCRM	Total Cost of Recovered Material
TPQOC	Total Purchased Quantity for Outsourced Component
TPWM	Total Purchased Weight for Material
TQC	Total Quantity of Components for Sub Module
TRMW	Total Recovered Material Weight
TTU	Total Time Usage
UCC	Unrecovered Component Cost
VAC	Variant Activity Cost
W	Width
WC	Weight of Component
WD	Working Days

Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: QUT Verified Signature

Date: 04 March 2016

List of Publications

A number of academic papers have been published or submitted as a part of this research. The list of publications is presented below:

- The, Jaya Suteja, Yarlagadda, Prasad K.D.V., Karim, Azharul, & Yan, Cheng (2013) A framework for life cycle cost estimation of a product family at the early stage of product development. *Advanced Materials Research, 605-607*, pp. 222-227.

- The, Jaya Suteja, Yarlagadda, Prasad K.D.V., Karim, Azharul, & Yan, Cheng (2014) An activity and resource advisory system for manufacturing process chains selection at the early stage of product development. *Advanced Materials Research, 834-836*(2014), pp. 1927-1931.

- Time-driven life cycle cost estimation system for product family design at the early stage of product development. (has been submitted to Journal of Engineering Design)

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“The fear of the Lord is the beginning of knowledge” (Proverbs 1:7)

Chapter 1: Introduction

This first section of this chapter outlines the background of this research. Then, it is followed by a summary of the research gaps addressed in this research and the formulated research questions, in Section 1.2. This chapter also describes the aim and the objectives in Section 1.3. After that, the innovation and the significance of this research are presented in Section 1.4. Finally, the last section provides an outline of the remaining chapters of this thesis.

1.1 BACKGROUND

Manufacturing companies are now under pressure to provide a variety of products in a shorter lead-time and in a cost effective way without sacrificing product quality and environmental considerations, in order to be competitive in the market (Ilgin & Gupta, 2010; King & Burgess, 2005; Wang, Song, Li, & Ng, 2007). Product family design has been proposed as an effective means to provide a variety of products in a cost effective way (Park & Simpson, 2008). The implementation of a product family design is also beneficial in reducing the costs related to environment conservation (Kwak & Kim, 2011; Kwak, Hong, & Cho, 2009). In general, a product family is defined as "a group of related products that is derived from a product platform to satisfy a variety of market niches" (Simpson, Siddique, & Jiao, 2006). All products within the group are related because they share common functions, features, components, technologies, processes, knowledge, people and/or relationships, which form a product platform (Simpson, et al., 2006).

A product family has five levels of components, which are part, product platform, variant, product variant, and product family levels. A product family consists of more than one product variant that share common elements. Each product variant is developed to satisfy customers from a certain market segment. Each product variant is comprised of product platform and variant. A product platform consists of several parts that form a common structure. A variant is a part or a collection of parts that differentiates one member of a product family from other members. A part is the lowest level component of a product family. Each part inherits the market segment attributes of the product variant to which it belongs.

An appropriate cost estimation system is required to evaluate the design of a product family. The cost estimation system is useful to assist in forecasting the profitability of the product family design, performing an economic evaluation of the technical choices design, and controlling various processes in the product family design (Gershenson & Zhang, 2003; Johnson & Kirchain, 2010; Marion, Thevenot, & Simpson, 2007; Park & Simpson, 2005, 2008; Siddique & Repphun, 2001; Wang, et al., 2007). It is also useful to support the trade-off between benefit and cost in designing the product family before a significant cost is incurred (Farrell & Simpson, 2010). As a product family has five levels of components, the cost estimation of each level of component is required.

Different product families could have different product structures (Du, Jiao, & Tseng, 2001; Jiao & Tseng, 2000). Even different product variants in the same product family could use different structures. Product structure is how the functions or components of a product are arranged in a hierarchical structure. Different product structures will influence the product family cost differently (Park & Simpson, 2005; Weustink, Ten Brinke, Streppel, & Kals, 2000). Therefore, the structure of a product family must be taken into account in estimating the cost of a product family.

The product family approach has been implemented by various types and sizes of companies. As various types and sizes of companies exist in the world, the cost estimation system must be able to be applied in different types and sizes of companies that implement different technologies and approaches. In addition, as technology is changing rapidly, the cost estimation system must be able to accommodate the changes or it will become unreliable (Patwardhan & Ramani, 2004). For that reason, the cost estimation system must be able to be implemented in different situations and take into account any changes.

Because of the increasing environmental awareness and the stricter regulations related to the environment, the cost estimation system must be able to estimate not only the pre-production and the production cost, but also the post-production cost, especially end of life cost of a product family (Park, Seo, Wallace, & Lee, 2002; Xu, Chen, & Xie, 2006). The estimation of the end of life cost is becoming important in performing an evaluation of the product family because the end of life cost now has a significant influence on the total cost of a product (Go, Wahab, Rahman, Ramli, & Azhari, 2011). For that reason, the cost estimation system must be able to estimate the life cycle cost of a product family, which involves all the incurred costs during the design, the production, the after sales, and the end of life stage.

The end of life cost of a product family depends on the selected end of life strategy of the product family. The end of life strategy of a product determines the end of life recovery process that will be conducted after the product is taken back. The end of life strategy of a product family should be selected on the sub module level because it is usually more economical for a product to be disassembled into its sub modules compared to into its part. Therefore, the cost estimation system must consider the end of life strategy of a product family on the sub module level in order to estimate the life cycle cost.

It is important to estimate the cost at the early stage of product development because a significant amount of the product cost is committed at this stage (Dowlatshahi, 1992). The early stage of product development refers to the stage after product planning and before the detail design stage. By performing the life cycle cost estimation at this stage, the cost could be adjusted as early as possible. As a result, decisions can be more easily (Cavalieri, Maccarrone, & Pinto, 2004). In addition, it is more feasible to reduce the cost at the early stage of product development without resulting in many difficulties that can be caused by late modification (Duverlie & Castelain, 1999; Karim, Ernst, & Amin, 2011). Therefore, the life cycle cost estimation of a product family should be performed at the early stage of product development.

At the early stage of product development, the available information is conceptual and not yet detailed. To find the available information at the early stage of product development, various attributes of a product family need to be explored and analysed to represent the product family. Based on the literature review, the available product family attributes at the early stage of product development are the market segment, the production volume, the product family structure, and the product family function (Fixson, 2006; Park & Simpson, 2008; Simpson, et al., 2006). In order to estimate the cost of a product family at the early stage of product development, the cost estimation system must be able to use these attributes as its input.

In summary, the growing implementation of a product family design has led to the need for various product family design support systems. In order to provide a variety of products in a cost effective way, it is required to develop a product family design support system that is able to estimate the life cycle cost of each component level of various structures of different product families at the early stage of product development.

Although the implementation of a product family approach could bring various benefits, it could raise the complexity at all stages during the product life cycle, including in estimating the life cycle cost at the early stage of product development. First, the implementation of a product family approach enlarges the portion of the indirect cost to the total cost and creates a significant error in estimating cost for the product family by using a traditional volume-based cost estimation technique (Horngren, Foster, & Datar, 1994). To reduce the error, the cost estimation system must be able to allocate the indirect cost properly. Second, the sharing component, process, resource, etc. between or among members of a product family could result in difficulty in allocating the cost of each member (Simpson, et al., 2006). The cost estimation system must be able to allocate the life cycle cost of each product variant and each component level of a product family. Third, as the cost estimation system should be able to estimate the life cycle cost of different structures of different product families, the system could require extensive time and effort in estimating the life cycle cost of various structures of a product family. To avoid this, the cost estimation system must be easy to be updated for different structures of different product families. Fourth, the implementation of the cost estimation system in different situations could require extensive time and effort in adapting process. The cost estimation system for a product family must be easily adapted to reflect any changes. Next, the life cycle cost of a product family is influenced by the end of life strategy of the product family. The end of life strategy of a product family should be determined on the sub module level. For that reason, the cost estimation system must consider various factors that influence the end of life of a sub module in estimating the life cycle cost. Last, in order to estimate the cost of a product family at the early stage of product development, the cost estimation system must be able to use the market segment, the production volume, the product family structure, and the product family function as its input.

1.2 RESEARCH GAPS AND RESEARCH QUESTIONS

Various cost estimation systems have been proposed for estimating the cost of a product and a product family. These systems implement various cost estimation techniques to estimate the cost of a product or a product family. The existing cost estimation techniques can be classified into four categories, which are intuitive, analogy, parametric, and analytic techniques (Niazi, Dai, Balabani, & Seneviratne, 2006). This research reviews various cost estimation techniques and analyses their implementation in allocating and estimating the cost of a product family (Section 2.5 and Section 2.6). Based on the review, the existing cost estimation techniques have their own difficulties in fulfilling the requirements in estimating the life cycle cost of a product family for design purposes (Gershenson & Zhang, 2003; Liu, Gopalkrishnan, Ng, Song, & Li, 2008; Marion, et al., 2007; Wang, Hou, Liu, & Wang, 2010; Wang, et al., 2007; Wei & Qin, 2011; Xiaoming, 2009; Xu, et al., 2006). To solve the difficulties, an activity-based costing technique has been proposed as a potential costing method for estimating the cost of a product family (Coughlin & Scott, 2013; Farrell & Simpson, 2010; Park & Simpson, 2005, 2008; Siddique & Repphun, 2001). However, this technique requires extensive time and effort to estimate the life cycle cost of various product families. Next, it still experiences some difficulties in estimating the life cycle cost of each component level of a product family in different types and sizes of companies that use different technologies and approaches. Then, it is difficult to be implemented at the early stage of product development because detailed information related to consumed activities and resources should be available. Last, it also needs an adaptation to suit the purpose as a design support system.

In summary, various systems found have been proposed in literature to estimate the life cycle cost of a product family. However, the systems do not provide satisfying answers for these several problems below.

The existing cost estimation systems have their own difficulties in fulfilling the requirement in estimating the life cycle cost of each component level of a product family for design purposes in different types and sizes of companies that use different technologies and approaches. Therefore, there is a need to implement a new technique that can be used to estimate the life cycle cost of each component level of a product family for design purposes, and adapted easily for different technologies and approaches.

This research has identified and categorised various costs incurred during the whole life cycle of a product (Section 2.2). The estimation of the post-production cost, particularly the end of life cost, is also important in understanding the potential benefits in remanufacturing and refurbishing. In addition, the influence of the end of life cost to a product cost, including a product family cost, is becoming significant, because the costs of product take back, product recovery, and product disposal are now being imposed on manufacturers. The decision related to the product take back, product recovery, and product disposal depend on the selected end of life strategy of the product. As a result, the end of life strategy has a significant influence in the end of life cost of a product family. The existing studies have determined the end of life strategy on the product or part level. As it is not feasible to determine the end of life strategy on the product or part level, the end of life strategy must be determined on the sub module level. In addition, the factors that can be used to determine the end of life of a sub module could be different compared to a product or a part. Considering this fact, there is a need to investigate various end of life strategies of a sub module, to develop a method to determine the end of life strategy of each sub module of a product family, and then to integrate the end of life strategy to estimate the life cycle cost of a product family.

Based on the review, the existing cost estimation systems experience difficulties in estimating the life cycle cost of different structures of different product families. Parametric and analogy techniques are not able to estimate the cost of different product families having different structures. Intuitive and analytic cost estimation techniques are able to estimate the cost of different product families but they require a large amount of information and time to develop the cost estimation system. Therefore, it is required that a method be developed that can reduce the required time and effort for updating process in estimating the life cycle cost for different structures of different product families.

A product family is represented by several attributes. These attributes influence the life cycle cost of a product family. In order to characterise a product family and estimate the life cycle cost of a product family, the attributes of a product family are required to be identified. This research attempts to explore and categorise all attributes of a product family and then analyse them in order to estimate the life cycle cost of a product family (Section 2.3). The available attributes of a product family required to design a product family at the early stage of product development has also been investigated. However, these attributes cannot directly be used to estimate the life cycle cost of a product family. How to use these available attributes of a product family to estimate the life cycle cost at the early stage of product development has not yet studied. In addition, most of the existing systems do not provide detailed information related to various factors and their influence on the cost. As a result, they cannot be used to assist in analysing the cost of a product family and evaluating its design. For that reason, it is important to find a way to transform the available information into the required information in order to estimate the life cycle cost and evaluate the design of a product family at the early stage of product development.

The primary research question addressed in this research is:

"How can the life cycle cost of each component level of different structures of product family be estimated for design purposes at the early stage of product development?"

The primary research question can be divided into four sub-questions below:

1. "How can the life cycle cost of each component level of a product family be estimated for design purposes without requiring extensive time and effort to adapt different technologies and approaches?"
2. "What are the end of life strategies for the sub module of a product family, how can the end of life strategy be determined for each sub module of a product family, and how can the end of life strategy be integrated to estimate the life cycle cost of a product family?"
3. "How can the life cycle cost be estimated for different structures of different product families with less time and effort in updating process?"
4. "How can the available information be transformed into the required information in order to estimate the life cycle cost and evaluating the design of a product family at the early stage of product development?"

1.3 AIM AND OBJECTIVES

The aim of this research is to develop a product family design support system, which is able to estimate the life cycle cost (design, production, after sales, and end of life cost) of each component level (part, product platform, variant, product variant, product family) of different product families at the early stage of product development.

In order to achieve the aim of this research, the following objectives have been identified:

1. To develop a life cycle cost model for design purposes, which is able to estimate the life cycle cost of each component level of a product family, without requiring extensive time and effort to adapt different technologies and approaches. It means that the cost model must be able to allocate and then calculate the life cycle cost to each component level of a product family. In addition, the model also must be able to be easily adapted for different technologies and approaches. This objective is achieved by proposing a methodology, as described in Section 3.3. In addition, Section 4.9 describes in more detail how the cost is allocated. How the model is used to estimate the life cycle cost is explained further in Section 4.10.

2. To develop a method to determine the end of life strategy for each sub module of a product family and then integrate the end of life strategy into the life cycle cost model in order to estimate the life cycle cost of a product family. The method to determine the end of life strategy for each sub module of a product family is explained in Section 3.4. The steps to generate the end of life strategy and its quantity are described further in Section 4.6. Section 4.10 shows how the end of life strategy is integrated into the life cycle cost model.

3. To develop a method that can reduce the required time and effort for updating process in estimating the life cycle cost for different structures of different product families. The method must be able to take into account different structures of different product families and estimate their life cycle cost with a less extensive database. In addition, it must require fewer steps to update any change. Section 3.5 explains the method that is proposed to estimate the

life cycle cost for different structures of different product families in less time and effort. Section 4.10 shows how this method is implemented.

4. To develop a system that is able to generate the required information in order to estimate the life cycle cost and evaluate the design of a product family at the early stage of product development. It means that the system must be able to transform the market segment, the production volume, the product family structure, and the product family function into the required information. The methodology to achieve this objective is presented in Section 3.6. The system that is proposed to generate the required information to estimate the life cycle cost at the early stage of product development is presented from Section 4.3 to Section 4.9.

5. To implement and then evaluate the proposed system. The methodology for evaluating the proposed system is described in Section 3.7. The development of the prototype of the proposed system, and how to implement it in order to evaluate the applicability of the proposed system, are presented in Chapter 5. Finally, the evaluation process of the proposed system is explained in Chapter 6.

To answer the primary research question, this research proposes a life cycle cost estimation system called time-driven life cycle cost estimation system, as a product family design support system, to solve the problem above. The proposed system is termed a time-driven life cycle cost estimation system, because it estimates the life cycle cost of a product family based on the consumption of time to conduct the activity required by the component level of the product family. The proposed cost estimation system is explained in Chapter 4.

1.4 INNOVATION AND SIGNIFICANCE OF THIS RESEARCH

The first innovation of this research is the implementation of an adapted time-driven activity-based costing technique to develop a life cycle cost model for design purposes. The time-driven activity-based costing technique that is originally used to estimate the cost for accounting purposes is adapted to estimate the cost for design purposes. The developed life cycle cost model can be implemented to allocate and then calculate the cost of each component level of a product family without requiring extensive time and effort to adapt different technologies and approaches. Second, this research develops a method to determine the end of life strategy of a product family on the sub module level. The method is developed to determine the end of life strategy of a product family on the sub module level, because it is not feasible to determine it on the product or part level. It is not realistic to determine the end of life strategy on product level because a product consists of more than one component that could have different attributes and end of life strategies. It is also not practicable to determine the end of life strategy on part level because it is usually less economical to disassemble a product into parts. Based on the developed method, the sub module quantity of each end of life strategy can be calculated and then integrated into the life cycle cost model to estimate the end of life cost of a product family. The next innovation is a method for estimating the cost of different structures of different product families based on the modular product architecture. By using the method, the life cycle cost of a certain component level of a product family can be calculated by summing all of its activity costs, the cost of its lower component level, and other costs consumed by the component level. As a result, implementation of the method can reduce the required time and effort for updating process in estimating the life cycle cost for different structures of different product families. Last, this research develops a system that is able to transform the information related to the market segment, the production volume, the product family structure, and the product family function at the early stage of product development, into the information related to the activities and resources required to estimate the life cycle cost and evaluate the design of a product family. This research conducts the first attempt to transform these four available attributes of a product family at the early stage of product development into the information related to activities and resources.

By using the proposed cost estimation system, the direct user, or in this case a designer in a manufacturing company, can evaluate the influence of the sub module or component selection, the product structure, the modularity design, the platform design, the manufacturing process selection, the assembly process selection, the procurement strategy selection, the outsourcing process selection, and the percentage of taken back product, to the life cycle cost of a product family at the early stage of product development. As a result, the manufacturing company will be able to evaluate various product family designs at the early stage of product development, adjust the product family cost as early as possible before a significant cost is incurred, and reduce the product family cost without resulting in many difficulties caused by late modification. In addition, the elaboration of the end of life aspects of a product family makes the proposed system ready to be able to take into account the influence of the end of life regulation to the life cycle cost of a product family. By inputting different percentages of the taken back product, the system is able to estimate the life cycle cost of the product family at different recovery targets on the end of life regulation. As a result, the proposed system also can be used to assist the manufacturing company to evaluate the impact of the end of life regulation to the end of life cost and analyse the cost and the benefit in conducting the remanufacturing and refurbishing processes at the early stage of product development. The outcome is that the manufacturing company is able to develop various cost effective product families in a shorter lead-time and minimise the destructive impact of the product family development on the environment.

1.5 THESIS OUTLINE

The first section of Chapter 2 of this thesis describes the definition and the characteristics of a product family. Then, the next section explains the importance of life cycle cost estimation for a product family. Section 2.3 describes the reason why it is important to estimate the life cycle cost at the early stage of product development and the available attributes of a product family required to estimate the life cycle cost at this stage. The difficulties in estimating the life cycle cost of a product family is then reviewed in the next section. The review of various existing cost estimation techniques in order to fulfil the requirements for estimating the life cycle of a product family at the early stage of product development is described in Section 2.5 and 2.6. At the end of this chapter, the research gaps in the literature are identified and the research questions are stated.

In Chapter 3, first, the aim and objectives of the research are formulated. Then, the innovation and the significance of the research are outlined in Section 3.2. This is followed by explanations about the methodology to estimate the life cycle cost, the methodology to determine the end of life strategy of a product family, the methodology to estimate the life cycle cost of different product structures, and the methodology to generate the required information in Section 3.3 to 3.6. Next, the methodology to evaluate the proposed solution is described in Section 3.7. Finally, the scope and limitation of the research is explained in Section 3.8.

The following chapter describes the time-driven life cycle cost estimation system framework that is proposed to address and fill the identified research gaps in Section 4.1. Then, this chapter explains how the system generates the components to carry out the required sub function and their attributes (Section 4.2 and Section 4.3), how the system generates all activities and resources consumed by the product family (Section 4.4 to Section 4.9), and how the system allocates and calculates the life cycle cost of each component level of product family (Section 4.10).

In Chapter 5, first, the development of the life cycle cost estimation system prototype is described. Then, the user interface of the life cycle cost estimation system prototype is presented in Section 5.2. After that, the steps to store the required data in the master and transaction databases of the system prototype are described in Section 5.3 and 5.4. Finally, the process to evaluate the system prototype is explained.

Chapter 6 starts with the description about the evaluation process. Then, it is followed by a description about the case study conducted in the collaborating company to evaluate the applicability of the proposed system. Then, the process of success evaluation is presented in Section 6.2. After that, the summary of the application and success evaluation are explained.

In the final chapter of this thesis, the summary of the research is described in Section 7.1. Then, the contribution of the research is explained in Section 7.2. Finally, the limitation and the scope of future research that need to be undertaken are addressed.

Chapter 2: Literature Review

This chapter begins by providing an insight of a product family (Section 2.1) and life cycle cost estimation (Section 2.2). This is followed in Section 2.3 by a review of literature about the importance of estimating life cycle cost at the early stage of product development, and then the difficulties in estimating the life cycle cost of a product family in Section 2.4. Various techniques to estimate the life cycle cost for a product family have been reviewed in Section 2.5. One of the cost estimation techniques, the Activity Based Costing technique, is reviewed further in Section 2.6. Finally, the research gaps, which are identified, are presented in the last section of this chapter.

2.1 PRODUCT FAMILY

For many years, manufacturing companies have been interested in minimising product cost, improving product quality, and shortening product lead-time. Recently, the growing importance of environmental awareness and stricter regulations related to the environment obligate manufacturing companies to integrate environmental considerations into all their activities (Ilgin & Gupta, 2010; King & Burgess, 2005). Concurrently, customer demands for customised products have increased significantly and the life cycle of a product becomes shorter and shorter (Wang, et al., 2007). This urges manufacturing companies to develop more variety in products for various customer segments in less time. As a result, manufacturing companies are now under pressure to provide a variety of products in a shorter lead-time and in a cost effective way, without sacrificing product quality and environmental considerations, to be competitive in the market.

Mass customisation is the most widely implemented approach to provide customised products at a reasonable cost in a shorter lead-time. Mass customisation is defined by Pine as variety and customisation through flexibility and quick responsiveness (Pine, 1993). The aim of this approach is to deliver a variety of product that fulfils customer needs while maintaining the mass production efficiency (Jiao & Tseng, 1999a). However, it is not is feasible to develop all viable product varieties because of some constraints within and outside the manufacturing companies. Mass customisation is constrained, not only by the natural laws and the technological limits, but also by the product cost or the price from the perspective of the customer (Zhang, Jiao, & Helo, 2007). In addition, focusing too much on individual customers and products could result in product proliferation, increased cost, and reduced profit margins (Zhang, et al., 2007). According to Luh, Chu, and Pan (2010, p. 225), “companies have to determine the appropriate degree of mass customisation to achieve an optimal level of cost and profit”.

Simpson (as cited in Park & Simpson, 2008) proposes that an effective means of fulfilling the requirements, to provide a variety of products in a cost effective way, is through a product family design. The implementation of a product family design is not only beneficial in the manufacturing and supply chain stages but also in the end of life stage (Kwak & Kim, 2011; Kwak, et al., 2009). According to Kwak and Kim (2011), the implementation of product family design may have an influence on profitability of end-of-life management. Product family design is a potential strategy to create the maximum recovery of a product (reuse, remanufacturing, or recycle) and to reduce the cost at the end of life stage. In addition, the implementation of a product family design also brings benefit in the after sales stage. As an architecture of a product influences its maintainability and reliability (Salonen, Holtta-Otto, & Otto, 2008), then the design of a product family could make it easy to be maintained in order to support after sales services.

Many definitions from different perspectives have been assigned to the concept of product family. In general, a product family is defined as “a group of related products that is derived from a product platform to satisfy a variety of market niches” (Simpson, et al., 2006, p. 3). Derived from various definitions of a product platform as cited by Simpson, et al. (2006), the group of products are related because they share common functions, features, components, technologies, processes, knowledge, people and/or relationships, which form a product platform. An example of a product family is the iPod family that consists of iPod shuffle, iPod nano, iPod touch, and iPod classic, as shown in Figure 1 (Apple Inc., 2012).

A product family has five levels of components, which are part, product platform, variant, product variant, and product family level. Accordingly, in this research, a product family is divided into these five levels of components. Each component level is related to each other by its market segment. A product family consists of more than one product variant that share common things. Each product variant is developed to satisfy customers from a certain market segment. Each product variant consists of product platform and variant. A product platform consists of several parts that form a common structure. A variant is a part or a collection of parts that differentiates one member of a product family from other members. A part is the lowest level component of a product family. Each part inherits the market segment attributes of the product variant to which it belongs.

Figure 2.1. iPod Family (Apple Inc., 2012)

2.2 LIFE CYCLE COST ESTIMATION

Designing a product family encompasses various issues from the front-end to the back-end (Simpson, et al., 2006). The front-end issues are related to how the product family design interacts with the customers and the market. These issues deal with the development, planning, selection, evaluation, leveraging of a platform and the positioning of a product family. The next issues are related to the improvement of the product family design. These issues address various methodologies to optimise a product platform and a product family. The back-end issues are related to the realisation of a product family and the process to produce a product family. These issues cover various techniques in estimating the cost, planning the process platform, and communalising the shape. This research mostly concerns the cost estimation in designing a product family.

According toTu, Xie, Fung, and Fung (2007), a rapid and accurate cost estimation and control system is needed to reduce the cycle time and the cost that is necessary for mass customisation. Related to a product family, a cost estimation system is useful to assist in estimating the profitability of the product family design, performing an economic evaluation of the technical choices design, and controlling other processes in the product family design (Gershenson & Zhang, 2003; Johnson &

Kirchain, 2010; Marion, et al., 2007; Park & Simpson, 2005, 2008; Siddique & Repphun, 2001; Wang, et al., 2007). It is also useful in performing the trade-off between the benefit and the complexity in optimising the product family design (Farrell & Simpson, 2010). Johnson and Kirchain (2011) give an example in their research illustrating that the increased product development cost, which is allocated in the development of the product families, can generate a significant cost saving. As a product family has five levels of components, the cost estimation of each level of component is required. Therefore, an appropriate cost estimation system is required to estimate the cost of each component level in order to assist in evaluating the design of a product family.

A product family could have various structures (Du, et al., 2001; Jiao & Tseng, 2000). Even different product variants in the same product family could use different structures. The product structure defines how the functions or components of a product are arranged in a hierarchical structure. It describes the relationship among functions or components of a product. Different product family structures will influence the product family cost differently (Park & Simpson, 2005; Weustink, et al., 2000). Therefore, the product family structure must be taken into account in estimating the cost of a product family.

The product family approach has been implemented by various types and sizes of companies. As various types and sizes of companies exist in the world, the cost estimation system must be able to be applied in different types and sizes of companies that implement different technologies and approaches. In addition, as technology is changing rapidly, the cost estimation system must be able to accommodate the changes or it will become unreliable (Patwardhan & Ramani, 2004). For that reason, the cost estimation system must be able to be implemented in different situations and take into account any changes.

The cost estimation system must be able to estimate the life cycle cost of a product family (Park, et al., 2002; Xu, et al., 2006). In a marketing perspective, product life cycle is defined as the stages in life span of a product, which are development, introduction, growth, maturity, and decline stages. In this research, the life cycle cost is not viewed from the marketing but from an engineering perspective. It involves all the incurred costs during the product design, the production, the product use, the support, and the disposal or recycling stage (Asiedu & Gu, 1998).

Depending on the point of view, the life cycle cost can be analysed from the perspective of different actors, e.g. supplier, manufacturer, user, and end of life actors' perspectives (Schau, Traverso, Lehmann, & Finkbeiner, 2011; Swarr et al., 2011). The life cycle cost can also be used to serve various purposes. According to Emblemsvåg (2003), the life cycle cost estimation serves three main purposes, which are as an effective engineering tool for providing decision support in design and procurement, to give useful cost insights in cost accounting and management, and as a design and engineering tool for environmental purposes. In this research, the life cycle cost is viewed from the manufacturer's perspective, with the main purpose of being used as an engineering tool for providing decision support in the design process.

To assist in design evaluation, various cost components incurred during the whole life cycle of a product have been identified from previous studies (Asiedu & Gu, 1998; Dhillon, 2009; Emblemsvåg, 2003; Fabrycky & Blanchard, 1991; H. Barringer, 2003; Korpi & Ala-Risku, 2008; Kusiak, 1993; Nasr & Kamrani, 2007; Roy, Souchoroukov, & Shehab, 2011; Schau, et al., 2011; Waghmode, Sahasrabudhe, & Kulkarni, 2010; Waghmode, 2014). First, this research categorises the product life cycle into four stages, which are research and development, production, after sales, and end of life stage. Then, the cost components are categorised based on the stages of product life cycle. The life cycle cost components and their stage categorisation are shown in Table 2.1.

Many researchers have proposed a variety of cost estimation techniques. However, the majority of the cost estimation techniques are proposed to estimate the cost incurred at the pre-production and the production stages. The estimation of the post-production costs, especially the end of life cost, is becoming important in performing an evaluation of the product family because the end of life cost now has a significant influence on the total cost of a product. The influence of the end of life cost is becoming significant because the costs of product take back, product recovery, and product disposal are now being imposed on manufacturers as a result of the increasing environmental awareness and the stricter regulations related to the environment (Go, et al., 2011). The estimation of the end of life cost is also important in understanding the potential benefits in remanufacturing and refurbishing.

Table 2.1. Life Cycle Cost Component

Life Cycle Stage	Life Cycle Cost Component
Research and Development Stage	Product Development Cost Product Design Cost Product Evaluation Cost
Production Stage	Production Planning Cost Inventory Control Cost Procurement Cost Material and Component Cost Manufacturing Cost Assembly Cost Packaging Cost Inspection/Quality Control Cost Inventory Cost Product Distribution/Transportation Cost Marketing Cost Sales Cost
After Sales Stage	Customer Service Cost Warranty Cost
End of Life Stage	Take Back Cost Disassembly Cost End of Life Cost

The decision related to the product take back, product recovery, and product disposal depend on the selected end of life strategy of the product. Therefore, the end of life strategy has a significant influence in the end of life cost of a product family. Various end of life strategies have been proposed for a product that is in its retirement stage (Germani, Luzi, Mandolini, & Marconi, 2014; Kwak & Kim, 2011; Kwak, et al., 2009; Rao & Padmanabhan, 2010; Remery, Mascle, & Agard, 2012; Rose, Stevels, & Ishii, 2000; Zakri & Atsuo, 2012; Zhang, Zhang, Jiang, & Wang, 2013; Ziout, Azab, & Atwan, 2014). However, the end of life strategy should not be determined on a product level because a product consists of more than one component that could have different attributes and end of life strategies. Other researchers have determined the end of life strategy on the part level (Zakri & Atsuo, 2012; Zhang, et al., 2013). This approach also has its limitations because a product is rarely disassembled into every single part at the retirement stage. A product is mostly disassembled into its sub modules because it is usually more economical compared to its part (Kwak, et al., 2009). For that reason, the cost estimation system must consider the end of life strategy of the sub module of a product family.

2.3 ESTIMATING LIFE CYCLE COST AT THE EARLY STAGE OF PRODUCT DEVELOPMENT

It is important to consider all design factors at the early stage of product development. The early stage of product development refers to the stage after product planning and before the product detail design stage. Any decisions at the early stage of product development are very crucial to the success of a product (Sturges, O'Shaughnessy, & Reed, 1993). For example, environmental issues should be considered, starting at the early stage of product development (Ramani et al., 2010) to ensure that the environmental activities performed are efficient, effective, and profitable (Go, et al., 2011; Kwak & Kim, 2010). Inappropriate decisions at this stage may result in inefficiency and even product failure (Sapuan, Ismail, Nukman, Hambali, & Rahim, 2011). A variety of methods have been proposed to help in making decisions at the early stage of product development (Karim, et al., 2011; Sapuan, et al., 2011; Sturges, et al., 1993; Subramaniam, Senthil Kumar, & Seow, 1999).

The estimation of the life cycle cost should be performed at the early stage of product development. According to Nevins and Whitney (as cited in Dowlatshahi, 1992), it is important to estimate the life cycle cost at the early stage of product development, because at least 70% of the product life cycle cost is committed at this stage. By performing the life cycle cost estimation at this stage, the cost could be adjusted as early as possible and as a result, decisions can be more easily made (Cavalieri, et al., 2004). In addition, it is more feasible to reduce the cost at the early stage of product development without resulting in many difficulties caused by late modification (Duverlie & Castelain, 1999; Karim, et al., 2011).

At the early stage of product development, the available information is conceptual and not detailed yet. Therefore, the estimation of the life cycle cost at the early stage of product development must be able to use the available information as its input. To find the available information at the early stage of product development, various attributes of a product family are explored and analysed to represent the product family (Krishnan & Ulrich, 2001). These attributes are embodied later into a product concept. The concept of product family can be interpreted from different views. In this research, the concept of a product family is interpreted from the view point of engineering. From this point of view, a product family consists of different product technologies and their associated manufacturability (Du, et al., 2001). In addition, the purpose of this research is to estimate the cost at the early stage of product development. For that reason, only the most relevant attributes of a product family are used to characterise each product family.

In this research, all attributes of a product family have been identified to characterise each product family based on the previous studies. According to Simpson, et al. (2006), four domains are encompassed in making decisions related to a product family, which are customer, functional, physical, and process domains. Later, Jiao, Simpson, and Siddique add one more domain, which is the logistics domain (Jiao, Simpson, & Siddique, 2007) as shown in Figure 2.2. However, as described above, recent trends suggest that after sales support and end of life domain should be also considered in designing a product family. Therefore, the identified attributes of a product family are categorised based on seven domains, as shown in Table 2.2.

Not all attributes required to design a product family are available at the early stage of product development. At the conceptual design stage, geometry and material of the product are not yet known (Creese & Moore, 1990). According to Pahl, Beitz, Feldhusen, and Grote (2007), the available product information are identified problems, required functions, working principles and structure. In addition, Zha (2005) describes that the available product information at the beginning of the conceptual design are functional requirements and relevant production requirements. Then, during the conceptual design stage, the information is transformed into critical design requirements. Based on the studies by Fixson (2006), Simpson, et al. (2006), and by Park and Simpson (2008), the available product family attributes at the early stage of product development are market segment, production volume, product family structure, and product family function. In order to estimate the cost of a product family at the early stage of product development, the cost estimation system must be able to use the market segment, the production volume, the product family structure, and the product family function as its input.

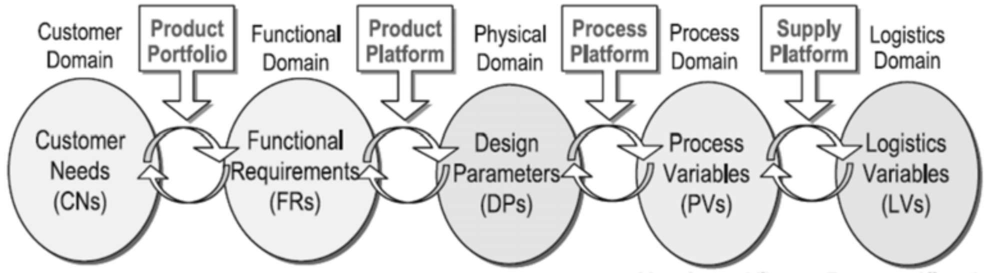

Figure 2.2. Product Family Domains (Jiao, et al., 2007)

Table 2.2. Product Family Attributes

Domains	Attributes	References
Customer	• Market Segment o Product Segment o Product Performance • Demand/Production Volume	(Jiao, et al., 2007; Kumar, Chen, & Simpson, 2009; Marion & Simpson, 2006; Park & Simpson, 2008)
Functional	• Function Type o Base Function o Variant Function • Technology/Concept o Input o Output • Product Specifications: structure, etc	(Blecker, Friedrich, Kaluza, Abdelkafi, & Kreutler, 2005; Jiao, et al., 2007; Otto & Wood, 2001; Simpson, et al., 2006; Zhang, Tor, & Britton, 2006)
Physical	• Product Attribute o Assembled Components o Quantity of Assembled Components o Assembly/Disassembly Sequence o Assembly/Disassembly Strategy • Component Attribute o Material o Shape o Main Dimension o Specific Feature o Size Tolerance o Surface Roughness o Material Property o Surface Finish	(Boothroyd, Dewhurst, & Knight, 2011; Jiao, et al., 2007; Jiao & Tseng, 1999a; Jiao, Tseng, Duffy, & Lin, 1998; Simpson, et al., 2006; Zhang, et al., 2007)
Process	• Manufacturing Process o Operation o Resource • Assembly Process o Operation o Resource • Disassembly Process o Operation o Resource	(Boothroyd, et al., 2011; Fixson, 2005; Hu et al., 2011; Jiao, et al., 2007; Simpson, et al., 2006; Zhang, et al., 2007)
Logistics	• Sourcing Strategy o Procurement Type o Supplier • Take back Strategy o Procurement Type o Supplier • Inventory Strategy • Distribution Strategy	(Fixson, 2005; Jiao, et al., 2007; Lamothe, Hadj-Hamou, & Aldanondo, 2006; Zhang, You, Jiao, & Helo, 2009)

Domains	Attributes	References
After Sales Support	• Warranty Strategy	(Ramdas, 2003; Salonen, et al., 2008)
End-of-Life	• End of life Strategy o Material EoL Strategy o Component EoL Strategy	(Go, et al., 2011; Kwak & Kim, 2010, 2011; Kwak, et al., 2009; Lee, Lye, & Khoo, 2001)

In summary, the growing implementation of a product family design has led to the need for various product family design support systems. In order to provide a variety of products in a cost effective way, it is required that a product family design support system is developed to estimate the life cycle cost of each component level of various structures of different product families at the early stage of product development.

2.4 DIFFICULTIES IN ESTIMATING LIFE CYCLE COST OF A PRODUCT FAMILY

Although the implementation of a product family approach could bring various benefits, it could raise the complexity at all stages during the product life cycle, including in estimating the life cycle cost of a product family. The implementation of a product family approach increases the range of products. The increased range of products increases the number of indirect activities, which benefit more than one product. As a result, it enlarges the portion of the indirect cost to the total cost. The increased portion of the indirect cost creates a significant error in estimating cost for product family by using a traditional volume-based cost estimation technique. The error becomes significant because a volume-based cost estimation technique assumes that the indirect cost is proportional to the volume of the product (Horngren, et al., 1994). In fact, the indirect cost does not always vary with production volumes. The assumption causes under costing for certain types of products and over costing for other products. To reduce the error, the cost estimation system must be able to allocate the indirect cost properly.

In addition, the implementation of a product family approach is more difficult compared to the implementation of multiple products because there are sharing components, processes, resources, etc. between or among members of a product family. The sharing component, process, resource, etc. between or among members could result in difficulty in allocating the cost of each member (Simpson, et al., 2006). It makes the cost estimation process for a product family much more difficult and could generate more errors than for an individual product and for multiple products. To reduce the error, the cost estimation system must be able to allocate the life cycle cost for each product variant of a product family. As the life cycle cost estimation of each component level is required in evaluating the design of the product family, the cost estimation system must also be able to allocate the life cycle cost of each component level of a product family.

Another problem that arises in estimating the cost of a product family is that different product structures will result in different costs (Park & Simpson, 2005; Weustink, et al., 2000). As the cost estimation system must be able to estimate the life cycle cost of different structures of different product families, the system could require extensive time and effort in estimating the life cycle cost of various structures of a product family. In addition, it is required to store complete information for each product platform, variant, and product variant. To avoid this, the cost estimation system must be easily updated for different structures of different product families.

The cost estimation system must be able to be applied in different types and sizes of companies. It must also be able to accommodate the trend of technology and reflect any change inside the company or it will become unreliable (Patwardhan & Ramani, 2004). The implementation of the cost estimation system in different situations could require extensive time and effort in adapting process. Therefore, the cost estimation system for a product family must be easily adapted to reflect any changes.

In addition, the life cycle cost of a product family is influenced by the end of life strategy of the product family. The end of life strategy of a product family should be determined on the sub module level. The factors that can be used to determine the end of life of a sub module could be different compared to a product or a part. Various factors are used to determine the end of life strategy of a product that is at the end of its life (Du, Cao, Liu, Li, & Chen, 2012; Rao & Padmanabhan, 2010; Rose, Ishii, & Stevels, 2001; Sabharwal & Garg, 2013; Tu, et al., 2007; Zwolinski, Lopez-Ontiveros, & Brissaud, 2006). Other researchers have proposed other factors to determine the end of life strategy of a part (Zakri & Atsuo, 2012; Zhang, et al., 2013). For that reason, the cost estimation system must consider various factors that influence the end of life of a sub module in estimating the life cycle cost.

Furthermore, the need to estimate the cost at the early stage of product development results in another problem in estimating the life cycle cost of a product family. In order to estimate the cost of a product family at the early stage of product development, the cost estimation system must be able to use the market segment, the production volume, the product family structure, and the product family function as its input (Fixson, 2006; Park & Simpson, 2008; Simpson, et al., 2006).

2.5 LIFE CYCLE COST ESTIMATION SYSTEMS FOR PRODUCT FAMILY DESIGN

A large number of systems for estimating the cost of a product have been proposed by many researchers, as summarised and reviewed by Asiedu and Gu (1998), Durairaj, Ong, Nee, and Tan (2002), Niazi, et al. (2006), Korpi and Ala-Risku (2008), Dhillon (2009), Huang, Newnes, and Parry (2012), and Waghmode (2014). The techniques used by the existing cost estimation systems can be divided into four classifications, which are intuitive, analogy, parametric, and analytic techniques (Niazi, et al., 2006). Intuitive cost estimation techniques use past experience to generate a body of knowledge related to the cost. This knowledge is then used to provide the required information to estimate the cost. Analogy cost estimation techniques estimate the cost based on the historical data of products with known cost. The historical data is used to establish a relationship between the cost and the values of certain selected variables. After that, the relationship can be used to estimate the cost of a new product. Parametric cost estimation techniques use statistical methodology to develop a cost estimation model. Then, the parametric cost model estimates the cost using certain critical parameters of the product. Analytical cost estimation techniques estimate the product cost by summing the cost of all the decompositions of the product. This method requires detailed information about the decomposition of the product to estimate the cost.

Many researchers use intuitive cost estimation techniques in estimating the cost of various products at the early stage of product development (Choi, Kelly, & Raju, 2007; Cicconi, Germani, Mandolini, & Marconi, 2014; Duverlie & Castelain, 1999; Madan, Rao, & Kundra, 2007; Shehab & Abdalla, 2002; Tang, Eversheim, & Schuh, 2004). Intuitive cost estimation techniques allow the cost estimation of different product families at the early stage of product development. These techniques provide a transparent estimation process which can assist in cost analysis. However, these techniques heavily rely on past data and previous experience to develop the cost estimation system. They have become unreliable because technology is changing rapidly. In addition, they are mostly used to estimate cost of an individual part or product because they require a large amount of information and time to develop the system. Estimating the cost of various product families that consist of a large number and various parts requires much larger amounts of information and time than estimating an individual part.

Other researchers suggest using analogy cost estimation techniques in estimating the cost at the early stage of product development (Cavalieri, et al., 2004; Ju, Zhou, & Xi, 2010; Liu, Gopalkrishnan, Quynh, & Ng, 2009; Seo, Park, Jang, & Wallace, 2002). Analogy cost estimation techniques are able to estimate the cost using conceptual and not detailed information as their input. In addition, this does not require much data. These techniques are able to estimate the cost of a new product when the extensive database are not available (Korpi & Ala-Risku, 2008). Several researchers show that the analogy cost estimation techniques are also able to estimate the life cycle cost of a product. Liu, et al. (2009) compare several regression models, which are artificial neural networks, support vector regression models, instance-based learning models, regression tree models, and local-weighted learning models, to estimate the life cycle cost. Their finding shows that artificial neural networks and support vectors are the best regression model techniques for cost estimating. Seo, et al. (2002) develop a cost estimation system that employs artificial neural networks to estimate the life cycle cost in conceptual design. The analogy cost estimation system has also been implemented in cost estimation of a product family (Xiaoming, 2009). Analogy cost estimation techniques could provide quick and easy life cycle cost estimation for a product family at the early stage of product development. However, the application of analogy cost estimation techniques is limited to those product families that have the same structure, because they use historical data of a certain product family. Analogy cost estimation techniques function as a black box in cost estimation and do not provide detailed information related to various factors and their influence on the cost. As a result, analogy cost estimation techniques cannot be used to assist in analysing the cost of a product family and evaluating its design.

Parametric cost estimation techniques are implemented by a number of researchers to estimate the cost of various products (Caputo & Pelagagge, 2008;

Cavalieri, et al., 2004; Duverlie & Castelain, 1999; Farineau, Rabenasolo, Castelain, Meyer, & Duverlie, 2001). Research by Wei and Qin (2011) uses the parametric technique in estimating specifically the cost of a product family. The parametric cost estimation techniques can be used in estimating the cost estimation of a product family at the early stage of product development. These techniques are able to estimate the life cycle cost of a product family as long as all critical parameters that influence the life cycle cost are identified. However, as they require and use previous data of a certain product family, they are not able to estimate the cost of different product families with different critical parameters. In addition, the accuracy of the technique is very low because they specify a complex product family with only a limited number of parameters.

Other researchers have proposed analytic cost estimation techniques for estimating the cost of a product family. A cost index structure, combined with generative and variant cost estimation methods, is proposed by Tu, et al. (2007) to estimate cost in mass customisation. The technique covers only production cost and poses some problems in estimating post production cost. Other researchers propose various applications of break down cost estimation technique for product family (Gershenson & Zhang, 2003; Marion, et al., 2007; Wang, et al., 2010; Wang, et al., 2007). These researchers were able to apply the analytic cost estimation techniques at the detail stage, but encountered difficulties when implementing it at the early stage of product development. Another study by Johnson and Kirchain (2010) proposes a process-based cost modelling as the cost modelling methodology to estimate fabrication, assembly, and development costs of the product. Similar to the previous techniques, process-based cost modelling also requires detailed information about the decomposition of the product in order to estimate the cost. A mathematical formulation to estimate the life cycle cost of a product in the on-going multi-generational product development is addressed by Cai and Tyagi (2014). Though this model can support engineering decision-making in a multi-generational product development environment, it cannot be implemented at the early stage of product development. One of the analytic cost estimation techniques, an activity based costing technique, is proposed by Coughlin and Scott (2013) to support market-driven top-down product family design. This technique is able to solve the difficulty in allocating the cost for each product variant, but technique is difficult to implement at the early stage of product development.

Four classifications of existing cost estimation techniques, which are intuitive, analogy, parametric, and analytic techniques, have been analysed. The result of the analysis is summarised in Table 2.3. Existing cost estimation techniques have also been analysed in order to estimate the life cycle cost of a product family at the early stage of product development. In order to assist in evaluating a product family, the cost estimation system must be able to estimate the life cycle cost of different structures of a product family, allocate the life cycle cost of each component level of a product family, be implemented at the early stage of product development, be adapted and updated easily. Each cost estimation technique has its own strengths and limitations in estimating the life cycle cost of a product family. The result of the requirement analysis is summarised in Table 2.4.

Table 2.3. Cost Estimation Techniques Analysis

Cost Estimation Techniques	**Strengths**	**Limitations**
Intuitive	-could be used to estimate the cost of different product families at the early stage of product development -able to assist in cost analysis	-require large amounts of information and time in developing a cost estimation system -unreliable for a new product because heavily rely on past data and previous experience
Analogy	-able to estimate the cost using conceptual and not detailed information as their input -provide a fast life cycle cost estimation for a product family at the early stage of product development	-limited to similar product families -do not provide detailed information related to various factors and their influence on the cost
Parametric	-able to estimate the cost using only several critical parameters at the early stage of product development	-estimate the cost of a certain structure of product family -the accuracy of the technique is very low
Analytic	-able to solve the difficulty in allocating the cost -could be used to estimate the cost of different product families	-require detailed information to estimate the cost

As an individual technique has difficulties in estimating life cycle cost of product family at the early stage of product development, a hybrid technique is applied in some studies as a possible solution. Liu, et al. (2008) built a hybrid intelligent system to estimate the product life cycle cost at the early design stage. This research applies activity-based costing and machine learning techniques to define and estimate various life cycle cost elements. An artificial neural network or support vector regression is applied if available activity and resource information are insufficient. An activity-based costing is applied if there are sufficient activity and resource information. This intelligent system can only estimate the cost of a product family that uses a certain product structure because the machine learning estimates the cost based on the historical data of a certain product family. Therefore, it cannot be used to assist in analysing the cost of a product family and evaluating its design.

Table 2.4. Requirement Analysis

Requirements	Intuitive	Analogy	Parametric	Analytic
Able to estimate the life cycle cost of different structures of a product family	Yes	No	No	Yes
Able to allocate the life cycle cost of each component level of a product family	Yes	No	No	Yes
Able to be implemented at the early stage of product development	Yes	Yes	Yes	No
Able to be adapted and updated easily	No	Yes	Yes	Yes

Another existing hybrid technique is proposed by Xu, et al. (2006). They propose a product life cycle costing system framework that uses case-based reasoning to build a new product model and activity-based costing to calculate the life cycle cost of the product. However, it only provides information about all activities consumed at the product level. As a result, it cannot be used to estimate the life cycle cost of each component level of a product family. Therefore, it cannot be used to assist in analysing the cost of a product family and evaluating product family design. In addition, it requires an extensive database to store the activities and resources information of all possible product models.

In summary, intuitive cost estimation techniques could be used to estimate the cost of different product families, but a large amount of information and time is required to develop the cost estimation system. Extensive time and effort are also required for them to be adapted and updated. Parametric and analogy cost estimation techniques are not able to estimate the cost of different product families having different structures. Other weakness of parametric and analogy techniques are that they experience difficulties to allocate the life cycle cost of each component level of a product family. Analytical cost estimation techniques are difficult to implement at the early stage of product development because they require detailed information about the decomposition of the product in estimating the cost. In addition, there is limited information available at post production especially at the end of life stage. Most of them are able to be adapted and updated easily but some of them experience difficulties. The existing hybrid cost estimation systems cannot be used to estimate the life cycle cost of each component level of a product family and estimate the cost of different product families having different structures. As a result, they cannot be used to assist in analysing the cost of a product family and evaluating its design.

2.6 ACTIVITY-BASED COSTING

One of the analytic cost estimation techniques, the activity-based costing technique, has been proposed by several researchers to estimate the cost of a product family. Siddique and Repphun (2001) employ an activity-based costing to estimate the design and development cost of the product family. Park and Simpson (2005) develop an activity-based costing framework for a product family, which consists of allocation, estimation, and analysis stages. Park and Simpson (2005) use the framework to estimate the production cost of a product family. Later, they refine the framework by developing cost modularisation in the activity-based costing system (Park & Simpson, 2008). Other research by Farrell and Simpson (2010) integrates an activity-based costing to their previous commonality improvement method in order to select the optimal product platform.

The activity-based costing technique estimates the cost by identifying the activities consumed by each product and the resources consumed by the activities. Then, the technique assigns the cost of each resource to all activities and the cost of each activity to all products, according to the actual consumption by each activity and product (Cooper & Kaplan, 1999; Garrison, Noreen, & Brewer, 2010; Horngren, et al., 1994). Activities are processes that produce an output by consuming substantial resources. Resources are the factors of production required to accomplish an activity (Brimson, 1997).

Hilton, Maher, and Selto (as cited in Park & Simpson, 2005) suggest five steps to measure production costs in a production system by using the activity-based costing technique, which comprises the identification of the resource spending at the four different activity levels (unit, batch, product, and facility), the measurement of the costs of resources used to perform activities, the identification of cost drivers and measure resource consumption rates, the assignment of the activity costs to products, and the analysis of the profitability of products at the four different activity levels.

Emblemsvåg (2003) proposes nine steps in implementing the activity-based costing technique. The first step is defining an activity library, which is represented as a hierarchy. Then, the time percentage in conducting each activity is identified. Next step is the determination of resource drivers. Based on the usage of the resource driver and the cost spent for the resource, the consumption intensity of the resource driver is calculated. After that, the cost of each activity is calculated by summing the cost of all resources consumed by the activity. The sixth step is the determination of activity drivers and grouping all activities that have the same activity driver. Then, the cost aggregation of the group is divided by the total usage of the activity driver to calculate the consumption intensity of the activity driver. The cost of each activity driver consumed by a product is equal to the multiplication of consumption intensity with the usage of each activity driver. Finally, the cost of a product can be calculated by summing the cost of all activity drivers consumed by the product.

In general, the activity based costing technique consists of eight steps, which are identifying all activities, identifying all resources to perform each activity, identifying the cost driver of each resource and its rate, defining the usage of each resource driver, calculating the cost of the activities, identifying the cost driver of each activity and its rate, defining the usage of each activity driver, and calculating the unit cost per product or service.

Several methods, which can be used to identify the activity, are analysis of historical records, analysis of organisation structure, identification of the process activities, or interviewing the person in charge (Brimson, 1997; Tornberg, Jämsen, & Paranko, 2002; Wang, Yang, & Shi, 2011). After all the activities are identified, they are modelled to ensure that they are considered. The activities could be modelled using IDEFO methodology, activity hierarchy, activity network, shop floor reference model or other tailor-made models (Ben-Arieh & Qian, 2003; Emblemsvag, 2001) (Barth, Livet, & De Guio, 2007).

A simple example in a bicycle manufacturing company could give a description about how to implement an activity-based costing. In the bicycle manufacturing company, several activities are performed to produce a bicycle, i.e. purchasing, storing, cutting, forming, welding, painting, distribution, etc. Each of the activities consumes several resources. For example, a welding activity consumes labour, welding machine, welding filler, electricity, etc. In order to calculate the cost of the bicycle, the cost of all resources consumed by each activity is summed and assigned as an activity cost. For example, the cost of labour, welding machine, welding filler, electricity, etc. consumed by welding activity is summed and assigned as the welding activity cost. Then, the cost of all activities performed to produce the bicycle, which are purchasing, storing, cutting, forming, welding, painting, distribution, etc., is summed and assigned as the cost of the bicycle.

The activity-based costing technique has a main difference compared to volume-based costing technique. The main difference is that it does not assume that the indirect cost is proportional to the volume of the product. In contrary, it allocates the indirect cost to a product based on the activity and resource consumed by the product. As a result, the activity-based costing technique assigns the indirect cost more accurately than the volume-based costing technique (Ben-Arieh & Qian, 2003; Kaplan & Robin, 1998).

Another advantage in using the activity-based costing technique for cost estimation is the ability to identify and analyse opportunities to reduce production costs by performing the activity analysis, which consists of activity elimination, activity reduction, activity selection, and activity sharing. The activity analysis can assist in identifying the inefficient activities and help to reduce the cost of the activity (Cooper & Kaplan, 1991). The activity-based costing technique can also be used as a communication tool to prevent product design and marketing from placing unreasonable demands on production (Turney, 1989).

All research described in the previous paragraphs implements an activity-based costing only for estimating the pre-production and/or the production cost. It is not discussed how to implement the activity-based costing to estimate the post-production cost. Research by Emblemsvag (2001) shows that an activity-based costing can be implemented in estimating the life cycle cost. However, he does not implement the activity-based costing at the early stage of product development. In his research, Emblemsvag (2001) utilised the activity-based costing in a platform supply vessel operation. Furthermore, Emblemsvåg (2003) implements an activity-based costing to estimate the life cycle cost of multiple toy products. Though it is applicable for multiple products, the approach does not tackle how to estimate the cost of a product family. It provides only information related to the activities and resources consumed by product instead of part. In addition, detailed information must be available in order to use the approach.

The activity-based costing technique can also be used to estimate the life cycle cost of a product family. Figure 2.3 shows how to estimate the cost of a product family. First, the activity-based costing technique assigns the cost of each resource to all activities according to the actual resource consumption by each activity. The cost of an activity can be calculated by summing all the resource costs assigned to the activity. Then, the cost of each activity is assigned to all component levels of the product family according to the actual activity consumption by each product. The cost of each component level of a product family can be calculated by summing all the activity costs assigned to the component level with the direct cost of the component level.

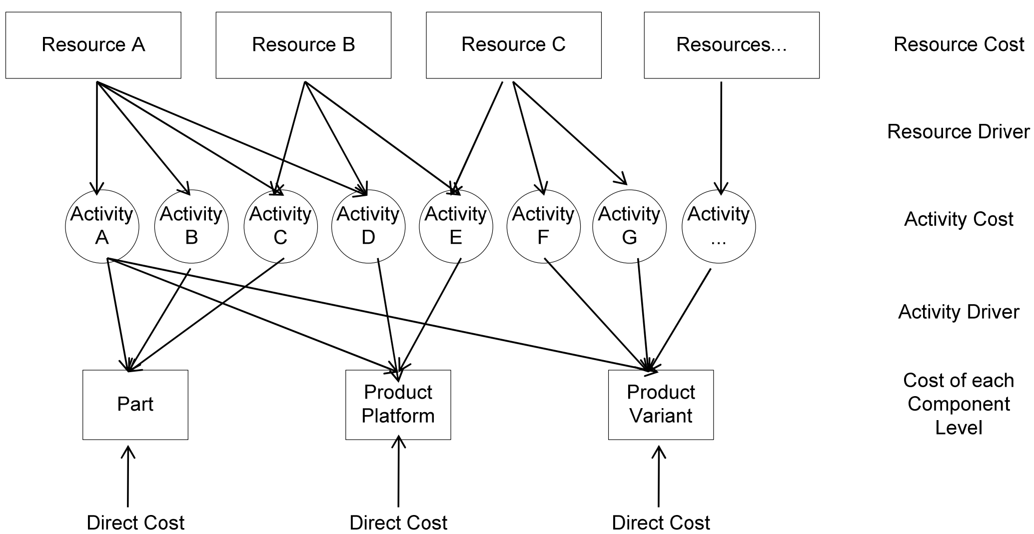

Figure 2.3. Activity Based Costing for Product Family

Based on the literature review above, the activity-based costing technique is considered as a potential costing method for estimating the cost of a product family. The activity-based costing technique is able to solve the difficulty in allocating the cost for each component level of a product family because it gives clear and consistent guidance on how to allocate the cost. In addition, the technique distributes the indirect cost, based on the activities and resources consumed by each product variant. As a result, it allocates the indirect cost more accurately to each product variant in a product family and reduces the error caused by the use of the traditional cost estimation method. Lastly, it is able to estimate the life cycle cost of different structures of different product families.

Even though the activity-based costing technique can solve some difficulties in estimating the life cycle cost of a product family, it still has several disadvantages. Although this technique is able to estimate the life cycle cost of different structures of different product families, it requires an extensive time and effort to estimate the life cycle cost of different product families. As the activity-based costing technique requires recollecting information related to the activities and resources, it is difficult and costly to be updated in order to reflect any changes. This technique also has difficulties in evaluating the life cycle cost in different types and sizes of companies because the consumed activities and resources will be different from one company to another company that use different technologies and approaches (Gunasekaran, 1999). Then, an activity-based costing technique is difficult to be implemented at the early stage of product development because detailed information related to consumed activities and resources should be available in using an activity-based costing technique. Last, the original aim of this technique is to estimate the cost of a product family for accounting purposes. It will need an adaptation to suit the purpose as a design support system.

2.7 RESEARCH GAPS IDENTIFIED

In the previous sections, the importance of a product family design and the necessity of a life cycle cost estimation for a product family have been described. After that, the difficulties in estimating the life cycle cost of a product family have been outlined. Then, analysis of various cost estimation techniques and systems has been carried out. According to the analysis, the existing systems do not provide satisfying answers for these several problems below.

- The existing cost estimation systems have their own difficulties in fulfilling the requirement of estimating the life cycle cost of each component level of a product family for design purposes in different types and sizes of companies that use different technologies and approaches. To solve these difficulties, the activity-based costing technique has been proposed as a potential costing method for estimating the cost of a product family. However, this technique still experiences some difficulties in estimating the life cycle cost in different types and sizes of companies that use different technologies and approaches, because they consume different activities and resources. Therefore, there is a need to develop a technique that can be used to estimate the life cycle cost of each component level of a product family for design purposes and can be adapted easily for different technologies and approaches.

- The end of life strategy has a significant influence in the end of life cost of a product family. The existing studies have determined the end of life strategy on the product or part level. As it is not feasible to determine the end of life strategy on the product or part level, the end of life strategy must be determined on the sub module level. In addition, the factors that can be used to determine the end of life of a sub module could be different compared to a product or a part. Considering this fact, there is a need to investigate various end of life strategies of a sub module, to develop a method to determine the end of life strategy of each sub module of a product family, and to integrate the end of life strategy to estimate the life cycle cost of a product family.

- The existing systems require extensive time and effort to estimate the life cycle cost of different structures of different product families. They need to store complete information for each product platform, variant, product variant, and product family. Therefore, it is required that a method is developed that can reduce the required time and effort for updating process in estimating the life cycle cost for different structures of different product families.

- Based on the literature review, the available attributes at the early stage of product development are the market segment, the production volume, the product family structure, and the product family function. However, these attributes cannot directly be used to estimate the life cycle cost of a product family. How to use these available attributes of a product family to estimate the life cycle cost at the early stage of product development has not yet studied. In addition, most of the existing systems do not provide detailed information related to various factors and their influence on the cost. As a result, they cannot be used to assist in analysing the cost of a product family and evaluating its design. For that reason, it is important to find a way to transform the available information into the required information in order to estimate the life cycle cost and evaluate the design of a product family at the early stage of product development.

It is clear from the analysis that none of the existing systems found in the literature are able to solve the difficulties in estimating the life cycle cost of a product family for design purposes at the early stage of product development. As stated in Section 1.2, for that reason, the aim of this research is to address the following primary research question:

"How can the life cycle cost of each component level of different structures of product family be estimated for design purposes at the early stage of product development?"

This primary research question above can be divided into four sub-questions below:

1. "How can the life cycle cost of each component level of a product family be estimated for design purposes without requiring extensive time and effort to adapt different technologies and approaches?"
2. "What are the end of life strategies for the sub module of a product family, how can the end of life strategy be determined for each sub module of a product family, and how can the end of life strategy be integrated to estimate the life cycle cost of a product family?"
3. "How can the life cycle cost be estimated for different structures of different product families with less time and effort in updating process?"
4. "How can the available information be transformed into the required information in order to estimate the life cycle cost and evaluating the design of a product family at the early stage of product development?"

To answer the research questions above, this research defines the aim and the objectives as outlined in Section 3.1. The methodologies to fill the research gaps are explained from Section 3.3 to 3.5. Based on the methodology explained in Chapter 3, this research proposes a life cycle cost estimation system in Chapter 4 that is used to achieve the aim of this research.

Chapter 3: Methodology

This chapter describes the aim and objectives, the innovations and significance of this research, and the methodology used to fill the research gaps. The proposed methodology will be elaborated further in Chapter 4. First, Section 3.1 describes the aim and objectives of this research and the proposed methodologies to achieve the aim and objectives. Then, the innovations and significance of this research are outlined in Section 3.2. The proposed methodology to answer the first research question is described in Section 3.3. This section discusses the methodology used in the research to estimate the life cycle cost of each component level of a product family and how to implement it. The methodology to determine the end of life strategy for each sub module of a product family is presented in Section 3.4. This methodology is used to answer the second research question. Section 3.5 explains the methodology to estimate the life cycle cost for different structures of different product families. This methodology is used to answer the third research question. The methodology to answer the fourth research question is presented in Section 3.6. This section discusses the selected types of knowledge-based systems and their design in order to generate the required information to estimate the life cycle cost. Section 3.7 addresses the methodology to evaluate the proposed solution. Finally, Section 3.8 explains the scope of the research.

3.1 AIM AND OBJECTIVES

The aim of this research is to develop a product family design support system which is able to estimate the life cycle cost (design, production, after sales, and end of life cost) of each component level (part, product platform, variant, product variant, product family) of different product families at the early stage of product development.

In order to achieve the aim of this research, the following objectives have been identified:

1. To develop a life cycle cost model for design purposes, which is able to estimate the life cycle cost of each component level of a product family

without requiring extensive time and effort to adapt different technologies and approaches.

2. To develop a method to determine the end of life strategy for each sub module of a product family and then integrate the end of life strategy into the life cycle cost model in order to estimate the life cycle cost of a product family.
3. To develop a method that can reduce the required time and effort for updating process in estimating the life cycle cost for different structures of different product families.
4. To develop a system that is able to generate the required information in order to estimate the life cycle cost and evaluate the design of a product family at the early stage of product development.
5. To implement and then evaluate the proposed system.

This research has proposed several methodologies in order to achieve its aim and objectives. Figure 3.1 shows the methodology that is implemented to answer each research question and achieve the research objectives. An adapted time-driven activity-based costing estimation technique is proposed to develop a life cycle cost model for design purposes in estimating the life cycle cost of each component level of a product family. As the life cycle cost is influenced by the end of life strategy, the end of life strategy generation method is proposed to generate the recovery activities and resources that are conducted at the end of life stage. Then, the generated recovery activities and resources are used to estimate the end of life cost using a time-driven activity-based costing technique. The modular product architecture approach is proposed to reduce the effort and time in accommodating different structures of different product families. This approach is used to determine the required information that must be generated by the knowledge-based system. In addition, this approach determines how the time-driven activity-based costing technique allocates the cost. The knowledge-based system is proposed to transform the conceptual, not detailed information at the early stage of product development, into the required information for estimating the life cycle cost using a time-driven activity-based costing technique. The application evaluation is proposed to evaluate whether the proposed methodologies can be used to achieve the objectives or not.

The detail of how each methodology can be used to fill the research gaps is explained from Section 3.3 to Section 3.7. Finally, all the methodologies are integrated to develop a product family design support system as explained in Chapter 4.

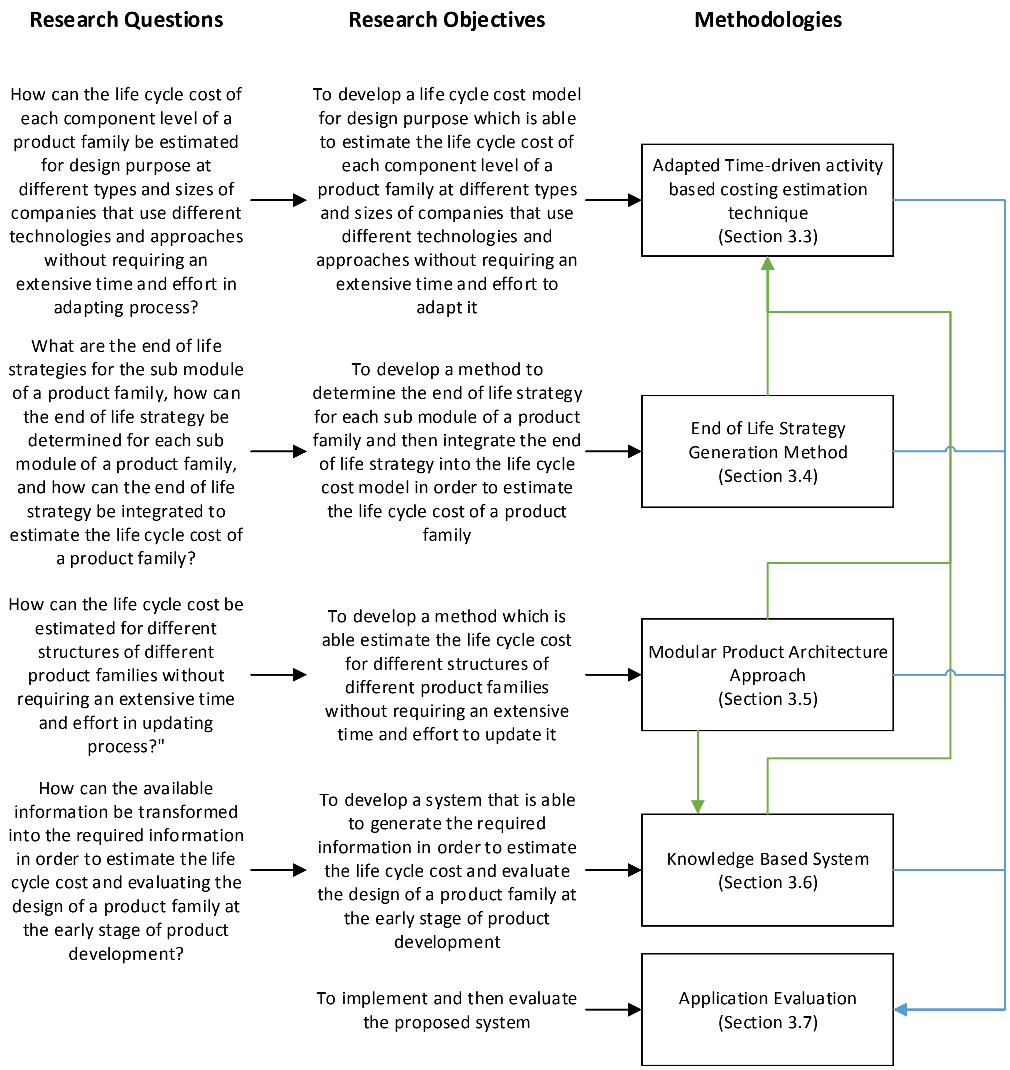

Figure 3.1. Research Methodologies

3.2 INNOVATIONS AND SIGNIFICANCE OF THIS RESEARCH

The existing systems have difficulties in allocating the life cycle cost of each component level of a product family because the implementation of a product family increases the range of products and the sharing component, process, resource, etc. between or among members of a product family. In addition, the existing systems need a lot of effort to evaluate the life cycle cost in different types and sizes of companies because the circumstances will be different from one company to another company, using different technologies and approaches. The first innovation of this research is the implementation of an adapted time-driven activity-based costing technique to develop a life cycle cost model for design purpose. The time-driven activity-based costing technique that is originally used to estimate the cost for accounting purposes is adapted to estimate the cost for design purposes. The developed life cycle cost model can be implemented to allocate and then calculate the cost of each component level of a product family without requiring an extensive time and effort to adapt different technologies and approaches.

Various end of life strategies are proposed for a product that is in its retirement stage. However, the end of life strategy should not be determined on a product level because a product consists of more than one component that could have different attributes and end of life strategies. Other researchers have determined the end of life strategy on a part level. This approach has also its limitation because a product is rarely disassembled into every single part at the retirement stage. As it is usually more economical to disassemble a product into its sub modules compared to into its part, the second innovation of this research is a method to determine the end of life strategy of a product family on the sub module level. Based on the developed method, the sub module quantity of each end of life strategy can be calculated and then integrated to the life cycle cost model to estimate the end of life cost of a product family.

Different product families could have different product structures. Even different product variants of a product family could use different structures. The existing systems are unable to estimate, or have difficulties in estimating the cost of different product families that have different structures. The other innovation of this research is a method for estimating the cost of different structures of different product families based on the modular product architecture. By using this method, the life cycle cost of a certain component level of a product family can be calculated by summing all of its activity costs, the cost of its lower component level, and other costs consumed by the component level. As a result, the implementation of the method can reduce the required time and effort for updating process in estimating the life cycle cost for different structures of different product families.

To allocate and calculate the life cycle cost of each component level of a product family at the early stage of product development, it is important to find a way to transform the available information into the required information. Most of the existing systems directly transform the available information into the cost. They do not provide detailed information related to various factors and their influence on the cost. As a result, they cannot be used to assist in analysing the cost of a product family and evaluating its design. Other studies have proposed various systems that can be used to assist in evaluating the design of a product family but do not pay attention to its structure. The next innovation is a system that is able to transform the information related to the market segment, the production volume, the product family structure, and the product family function at the early stage of product development, into the information related to the activities and resources required to estimate the life cycle cost and evaluate the design of a product family. This research conducts the first attempt to transform these four available attributes of a product family at the early stage of product development into the information related to activities and resources. The information related to the activities and resources can be used in estimating the life cycle cost. In addition, the generated activities and resources information can also be used in evaluating the design of a product family.

The proposed system can be used to estimate the total cost incurred at each stage of the product life cycle, estimate the life cycle cost by inputting conceptual and not detailed information, estimate the life cycle cost of each component level of a product family, and estimate the life cycle cost for different product families. By using the proposed cost estimation system, the direct user, or in this case a designer in a manufacturing company, can evaluate the influence of the sub module or component selection, the product structure, the modularity design, the platform design, the manufacturing process selection, the assembly process selection, the procurement strategy selection, the outsourcing process selection, and the percentage of taken back product to the life cycle cost of a product family at the early stage of product development. As a result, the manufacturing company will be able to evaluate various product family designs at the early stage of product development, adjust the product family cost as early as possible before a significant cost is incurred, and reduce the product family cost without resulting in many difficulties caused by late modification. In addition, the elaboration of the end of life aspects of a product family makes the proposed system ready to take into account the influence of the end of life regulation to the life cycle cost of a product family. By inputting different percentages of the taken back product, the system is able to estimate the life cycle cost of the product family at different recovery targets on the end of life regulation. As a result, the proposed system also can be used to assist the manufacturing company to evaluate the impact of the end of life regulation to the end of life cost and analyse the cost and the benefit in conducting the remanufacturing and refurbishing processes at the early stage of product development. The outcome is that the manufacturing company is able to develop various cost effective product families in a shorter lead-time and minimise the destructive impact of the product family development on the environment.

3.3 METHODOLOGY FOR ESTIMATING LIFE CYCLE COST

This section describes the time-driven activity-based costing estimation technique that is proposed to estimate the life cycle cost for design purposes. This section also presents how the proposed technique is adapted to allocate and then calculate the cost of each component level of a product family without requiring extensive time and effort to adapt different technologies and approaches. This section also explains how the technique is implemented to ensure that it is able to estimate the life cycle cost of a product family. Section 4.9 describes in more detail the method to allocate the cost. The model to estimate the life cycle cost is explained further in Section 4.10.

3.3.1 Time-driven Activity-Based Costing Technique

One of the analytic cost estimation techniques, the activity-based costing technique, has been proposed by several researchers to estimate the cost of a product family. It is considered as a potential costing method for estimating the cost of a product family. The activity-based costing technique is able to solve the difficulty in allocating the cost for each component level of a product family. This technique allocates the indirect cost more accurately to each product variant in a product family and reduces the error caused by the use of traditional cost estimation method. It is also able to estimate the life cycle cost of different structures of a product family.

However, the activity-based costing technique is difficult to implement at the early stage of product development, because detailed information related to consumed activities and resources must be available to estimate the cost by using the activity-based costing technique. The data collection process is also very expensive to be conducted, especially in achieving high accuracy results, because lots of fine and low level data are required. The activity-based costing technique requires recollecting data to reflect any change. As a result, it is difficult and costly to update the activity-based costing model in reflecting changes. This technique also has difficulties in being used to evaluate the life cycle cost of different types and sizes of companies, because the consumed activities and resources will be different from one company to another company that use different technologies and approaches. Lastly, it will need an adaptation to suit the purpose as a design support system.

To improve the activity-based costing technique and solve the problems in implementing the activity-based costing technique for a product family, a time-driven activity-based costing technique is proposed. The time-driven activity-based costing technique allocates the cost of resource groups to a product based on the time required to perform an activity (Kaplan & Anderson, 2013; Kaplan & Anderson, 2004). By using this technique, various costs that are spent to produce a product, such as process cost and procurement cost, are estimated based on the time required to perform the activities and the rate of the consumed resources. Figure 3.2 shows the implementation of a time-driven activity-based costing technique to estimate the cost of a product family. First, the technique assigns the resource expenses to each department and calculates the rate of each resource in each department. Then, all activities consumed by each component level of a product family are identified and their required time is estimated. After that, all activity costs consumed by each component level are calculated. Finally, the cost of each component level is calculated by summing the cost of all activities consumed by the component level with the direct cost of the component level.

The differences of the time-driven activity-based costing technique and the traditional activity-based costing technique are shown in Table 3.1 (de Arbulo, Fortuny, García, de Basurto, & Zarrabeitia, 2012; Everaert, Bruggeman, Sarens, Anderson, & Levant, 2008; Kaplan & Anderson, 2013; Monroy, Nasiri, & Peláez, 2014; Öker & Adigüzel, 2010; Tse & Gong, 2009). The first technique is simpler than the second technique because its main cost driver is only time. The data collection process of the first technique is less time consuming and less costly compared to the second technique because the first technique eliminates the need to collect data for allocating resource costs to activities and cuts the length of the data collection process. It is also easier to update the first technique for various approaches and technologies. If there is any change in technology and approach, the first technique only needs to modify the activity, the time consumed by the activity, the resource quantity, and the resource rate of the related department. Therefore, the first technique is easily adapted for different companies using different technologies and approaches. As first technique excludes the idle resource and it reduces the subjectivity, its accuracy is better than the second technique. The first technique is easily modified in order to reflect changes in the operating conditions, because it reduces significantly the need for recollecting data. For an example, it is easy to modify the time of an activity if there is any change in the activity. The required time is simply estimated for the activity.

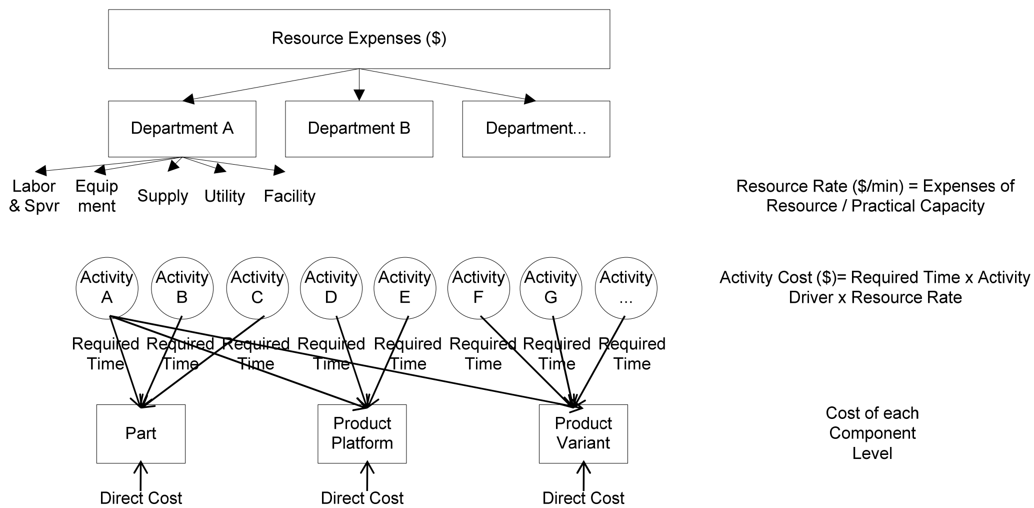

Figure 3.2. Time-driven Activity-Based Costing Technique for Product Family

The required steps to implement the time-driven activity-based costing technique for estimating the cost of a part, are identifying resource groups and the costs of each resource group, allocating the costs of non-operating resource group to operating resource group, estimating the practical capacity of each operating group, calculating capacity cost per time unit, identifying the activities that consume the resources, identifying the drivers of each activity, estimating the required quantity of each activity driver for each part, defining the required time to perform each activity for each part, calculating the total time of each activity for each part, calculating each resource cost for each activity for each part, calculating the activity cost for each part, and calculating cost of each part (Everaert, et al., 2008; Kaplan & Anderson, 2013; Öker & Adigüzel, 2010; Tse & Gong, 2009).

Table 3.1. Time-driven Activity-Based Costing Versus Traditional Activity-Based Costing

Time-driven activity based costing	Activity based costing
The main cost driver is time	Different cost drivers are assigned for different resources
The cost of the resource is not allocated to the activity before relating the activity to different products or services	The cost of the resource is allocated to different activities and then the cost of the activity is allocated to different products or services
The time estimation can be obtained not only by direct observation and interviews but also through engineering techniques	The resource expense assigned to an activity is determined through interviews, time logs, and direct observation of the amount or percentage of time people spent on various activities
The idle resource is not allocated to any resource group cost	It assumes that the resource is working at full capacity
It do not have to recollecting all data to reflect changes in their operating conditions	To update the model, it requires to recollect all data to reflect changes in a company's operations

A resource group is a set of resources that is grouped together based on a certain similarity. In this research, the resources are grouped according to the department in a company. The cost of each resource group consists of the cost of labour and supervisor, the cost of equipment, the cost of supplies, the cost of utilities, and the cost of facilities. The resourced groups can be categorised into operating and non-operating resource groups. Non-operating resource groups consist of all resources in all departments whose activities do not directly influence the production volume, such as human resources, maintenance, and facility management departments. The cost of the non-operating resource group is allocated to the cost of the operating resource group based on the work done for the operating resource group. Then, the capacity cost per time unit or capacity cost rate of each operating resource group is calculated based on the practical capacity of the operating resource group. The practical capacity is the full capacity minus the unused capacity. To calculate the capacity cost per time unit, the cost of the resource group is divided by the practical capacity of resource group.

The activity information must be general information so it can be used in different manufacturing companies. To generate the activity information, the identified activities are aggregated after they are identified. The detailed level of activity aggregation is determined to make sure that it is sufficient for the implementation of time-driven activity-based costing technique. To identify the resources consumed by each activity, the activity is embedded in the resource group or in this case the department. The resources consumed by the activity are all resources in the embedded department. In addition, the activity driver is a factor that influences the cost of the activity. The quantity of the activity driver is the required amount or number of the activity driver consumed by a part.

After the identification of the activity, the activity driver, the quantity of the activity driver, and the required activity time, the total required time of each activity for each part is calculated by multiplying the quantity of each activity driver for each part with the required time to perform each activity for each part. Then, the resource cost of each activity for each part is calculated by multiplying capacity cost rate for each resource with the total time of each activity for each part. The activity cost for each part is the summation of resource cost of each activity for each part. Finally, the part cost can be calculated as the summation of activity cost and the other costs consumed by each part such as material cost, storage cost, etc.

The methodology in implementing a time-driven activity-based costing technique for accounting purposes is not the same as the methodology for design purposes at the early stage of product development. For accounting purposes, activity information is taken from the activity performed in the shop floor or office. The cost of these activities can be allocated and calculated easily for each part or product. Meanwhile, for design purposes, the required activity is not known yet. As a result, the activity required by each part or product must be identified before the cost can be allocated and calculated for each part or product. In addition, the implementation of a time-driven activity-based costing technique for a product family is also different compared to that for a single part or product. As a product family consists of five levels of components that need to be put into a consideration, then the activity cost must be allocated and calculated for each component level.

Therefore, the time-driven activity-based costing technique must be adapted to be able to estimate the cost of each component level of a product family for providing decision support in the design process at the early stage of product development. The proposed implementation of the time-driven activity-based costing technique for design purposes is shown in Figure 3.3. First, the product family must be broken down into its component levels. Then, the activities required by each component level, with their activity drivers, are identified and allocated. The total required time of each activity is calculated by multiplying the quantity of each activity driver with the required time to perform each activity. After that, the resources are grouped according to the available departments and the resources rate of each department is calculated. Then, all activity costs of each component level are calculated. Finally, the cost of each component level of a product family can be calculated by summing the cost of all activities consumed by the component level with the direct cost of the component level.

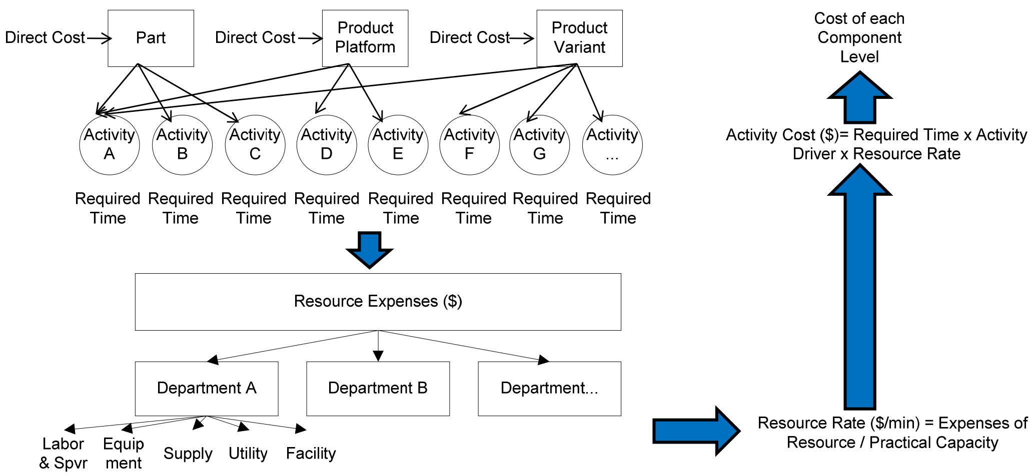

Figure 3.3. Time-driven Activity-Based Costing Technique for Product Family Design

By implementing the adapted time-driven activity-based costing technique, the life cycle cost to each component level of a product family can be allocated based on the time required to perform an activity. In addition, different approaches and technologies can be adapted with less time and effort. As different approaches require different activities and required time, the user needs to modify the activity and the time consumed by the activity to reflect different approaches. As different technologies require different quantity and rate of labour, equipment, supply, utility, and facility, the user needs to modify the resource quantity and the resource rate of the related department to reflect different technologies. These modifications do not require recollection of various resource driver data and its usage for each activity. Therefore, it reduces significantly the effort and time in adapting different approaches and technologies.

Even though the time-driven activity-based costing technique can solve several problems in implementing the traditional activity-based costing technique, it is still difficult to implement the proposed technique to estimate the life cycle cost at the early stage of product development. The implementation of the time-driven activity-based costing technique requires the information related to the activities and the resources that are not available at the early stage of product development. To estimate the life cycle cost of a product family at the early stage of product development, this research attempts to integrate the time-driven activity-based costing technique with another system that can generate the required information. Section 3.5 describes how to generate the required information to be used by the time-driven activity-based costing technique in estimating the life cycle cost at the early stage of product development.

3.3.2 Estimating Life Cycle Cost

To ensure that the time-driven activity-based costing technique is able to estimate the cost at each stage of a product family, it is implemented as described in Figure 3.4.

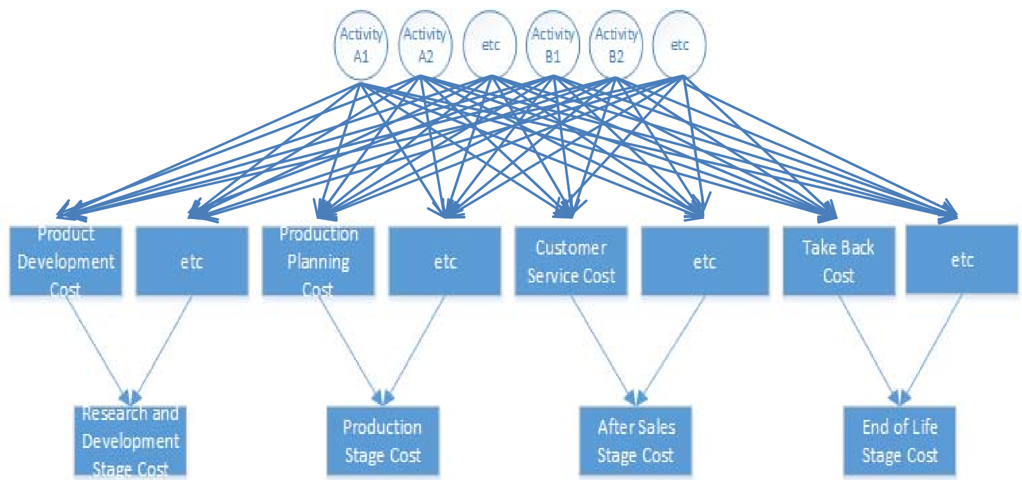

Figure 3.4 Estimating Life Cycle Cost

As already described in Section 2.2, this research categorises the product life cycle into research and development, production, after sales, and end of life stages. The cost of each stage consists of several cost components, as shown in Table 2.1. The cost of each activity, which is calculated by using the time-driven activity-based costing technique, then is categorised according to these cost component categories. The category of each activity cost is determined by using cause and effect analysis. Next, the cost of all activities in the same cost component categorisation is summed. Finally, all costs of the same stage categorisation are summed as the life cycle cost of each stage. The implementation of the proposed cost estimation technique is described in more detail in sub section 4.10

3.4 METHODOLOGY FOR DETERMINING THE END OF LIFE STRATEGY FOR A PRODUCT FAMILY

The estimation of the post-production costs, especially the end of life cost, is becoming important in performing an evaluation of the product family because the end of life cost now has a significant influence on the total cost of a product. End of life stage of a product is a stage in which a product is supposed to retire because its life span has been exhausted. At this stage, an end of life strategy must be determined to reduce the bad impact of the product for the environment. The end of life strategy of a product determines the end of life recovery process that will be conducted after the product is taken back. The end of life strategy has a significant influence in the end of life cost of a product family. The cost estimation system must consider the end of life strategy of a product family on the sub module level. Therefore, this research investigates and then proposes various end of life strategies for a sub module.

A sub module could be a part or a sub assembly type of sub module. Therefore, the end of life strategies are categorised into end of life strategies for part type sub module and end of life strategies for sub assembly type sub module. The viable end of life strategies for part type consist of reuse as part, reuse as part with reconditioning, reuse as part with repairing, and recover as material strategies. For sub assembly type of sub module, the viable end of life strategies are reuse as sub assembly, reuse as sub assembly with reconditioning, reuse as sub assembly with repairing, reuse as sub assembly with replacing, and recover as material strategies. If the sub module is recovered as a material, four end of life strategies for a material which can be conducted are recycle, incinerate, treat as hazardous material, and landfill strategies.

After being recovered, the sub module and material could be used in two further processes, which are remanufacturing or refurbishment process (Ijomah, Childe, & McMahon, 2004; King & Gu, 2010; Kwak & Kim, 2011; Lund & Hauser, 2010; Rose, et al., 2001; Saavedra, Barquet, Rozenfeld, Forcellini, & Ometto, 2013; Wang & Tseng, 2010). In this research, the recovered sub module and material are assumed to be used only in a remanufacturing process. It means that the recovered sub module and material are not sold individually but used as a component or material of any manufactured product.

The proposed framework to generate the end of life strategy on the sub module level is shown in Figure 3.5. First the taken back product is inspected and sorted, whether it is still working or not. Then, the taken back product is disassembled into its sub modules. A pre-treatment process will be conducted before the taken back product is disassembled if it is required. After that, the disassembled sub modules are sorted into part type and sub assembly type of sub module. These two types of sub module have their own framework for determining their end of life strategy. The framework to generate the end of life strategy for the sub assembly type sub module is explained in Section 3.4.1. Section 3.4.2 describes the framework to generate the end of life strategy for the part type sub module. Finally, section 3.4.3 gives details about the framework to generate the end of life strategy for the unrecovered component. Sections 4.6 and 4.10 show how the end of life strategy is integrated into the life cycle cost model.

3.4.1 Generating End of Life Strategies for Sub Assembly Type of Sub Module

First, the sub assembly type of sub module is categorised, whether it was permanently assembled or not previously. The process to disassemble the permanently assembled sub assembly might cause damage to the sub module. Therefore, if it was permanently assembled, it will be inspected and sorted, whether it is repairable or not. If it is repairable, then it will be further disassembled and the damaged part will be repaired. If it is not repairable, then it will be further disassembled and its unrepairable part will be replaced with a new part.

If the sub assembly type sub module was not permanently disassembled and it is collected from the working taken back product, it will be inspected and sorted, whether it has any wear or tear. If the sub module has no wear or tear, it does not need any further process. If it has any wear or tear, then it will be inspected whether it is able to be reconditioned or not. If it is able to be reconditioned then it will be further disassembled and its wear or tear part will be reconditioned. If it is not able to be reconditioned, then it will be further disassembled and its wear or tear part will be replaced with a new part.

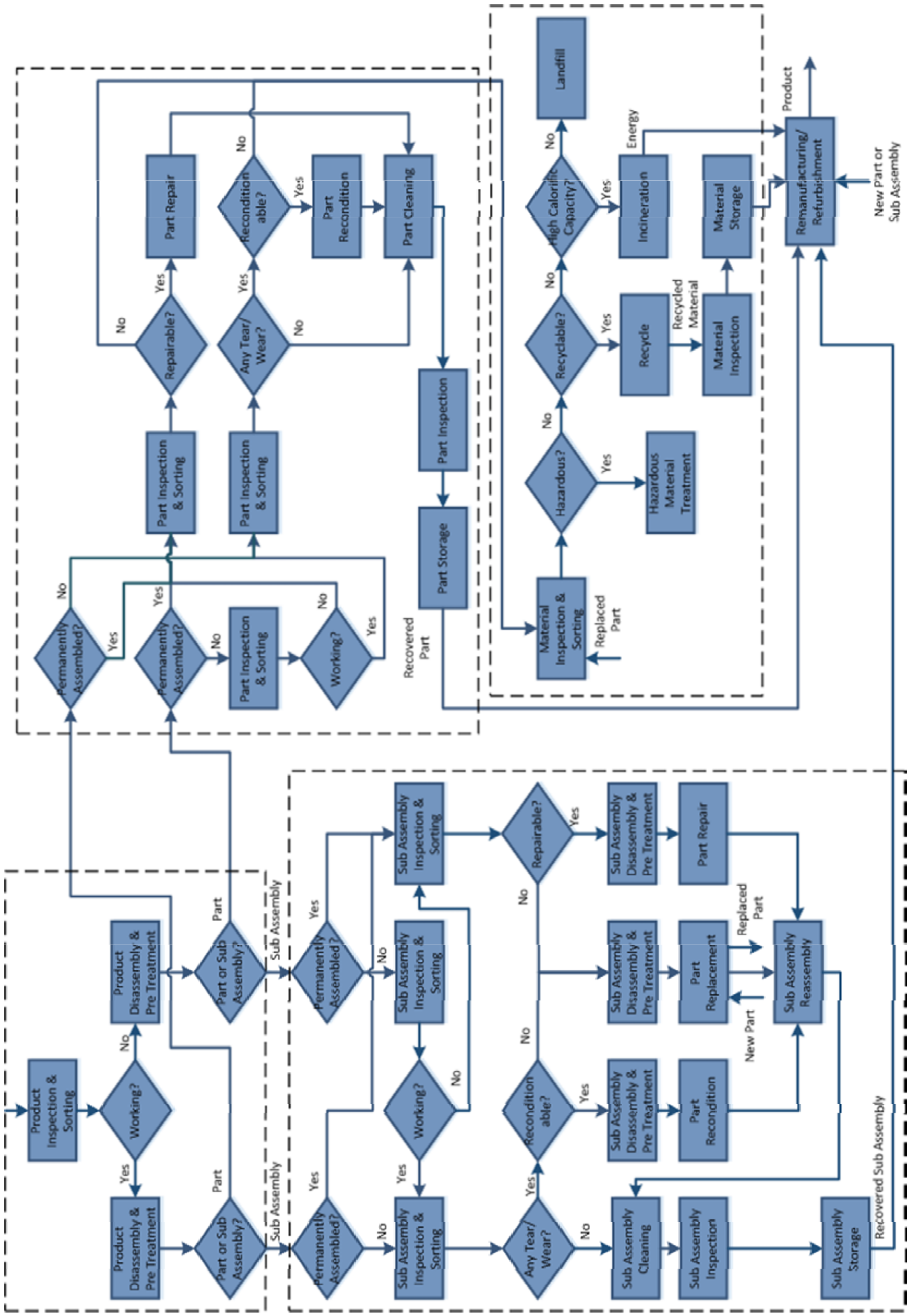

Figure 3.5. Framework to Generate End of Life Strategy

If the sub assembly type sub module was not permanently disassembled and it is collected from the non-working taken back product, it will be inspected and sorted whether the sub module is working or not. If it is working, it will be inspected and sorted whether it has any wear or tear. The next step is the same as described for the sub module collected from the working taken back product above. If it is not working, then it will be inspected and sorted whether it is repairable or not. The next step is the same as described for the sub module that is permanently assembled above.

Then, the reconditioned, the replacement, and the repaired part of the sub assembly type sub module are reassembled into a recovered sub module. After that, the recovered sub module is cleaned, inspected, and stored. The recovered sub module is used as a recovered sub assembly in the remanufacturing process. Meanwhile, the replaced part of the sub assembly type sub module will be used as recovered material. The sub assembly type of sub module that is bought from another party cannot be reconditioned or repaired because no competency or resource is available to do the processes. As a result, all parts of the sub assembly type of outsourced sub module that cannot be reconditioned or repaired will be used as recovered material.

If the recovered sub assembly type sub module does not need any further process, then the end of life strategy for the sub module is “reuse as sub assembly”. If it needs a reconditioning process, then the strategy is “reuse as sub assembly with reconditioning”. The “reuse as sub assembly with repairing” strategy is used for the recovered sub module that requires repairing. And, the “reuse as sub assembly with replacing” strategy is used for the sub module that requires replacing.

3.4.2 Generating End of Life Strategies for Part Type of Sub Module

First, the part type of the sub module is categorised, whether it was permanently assembled or not. If it was permanently assembled, then it will be inspected and sorted, whether it is repairable or not. If it is repairable, then it will be repaired. If it is not repairable, it will be used as recovered material.

If the part type sub module was not permanently assembled and it is collected from non-working taken back product, then it will be inspected and sorted, whether it is working or not. If it is not working, then it will be inspected, whether it is repairable or not. If it is repairable, then it will be repaired. If it is not repairable, it will be used as a recovered material. If it is working, then it will be inspected and sorted, whether it has any wear or tear. If it has any wear or tear, then it will be inspected, whether it can be reconditioned or not. If it is recondition able, it will be reconditioned. If it is not recondition able, it will be used as a recovered material.

If the part type sub module was not permanently assembled and it is collected from working taken back product, then it will be inspected and sorted, whether it has any wear or tear. If the sub module has no wear or tear, it does not need any further process. If the sub module has any wear or tear, the next step is the same as described for the sub module that is working above.

Then, the unprocessed, the repaired, and the reconditioned part type sub modules are cleaned, inspected, and stored. The recovered sub module is used as a recovered part in a remanufacturing process. Meanwhile, the part type of sub module that is bought from another party cannot be reconditioned or repaired because no competency or resource is available to do the processes. As a result, all part type of outsourced sub modules that cannot be reconditioned or repaired will be used as recovered material.

If the recovered part type sub module does not need any further process, then the end of life strategy for the sub module is “reuse as part”. If it needs a reconditioning process, then the strategy is “reuse as part with reconditioning”. The “reuse as part with repairing” strategy is used for the recovered sub module that requires repairing process.

3.4.3 Generating End of Life Strategies for Unrecovered Component

As described above, the replaced part, the unrepairable part, and the part that cannot be reconditioned are used as recovered material. The end of life strategy for these parts is determined based on their material. First, each part is inspected whether it contain a hazardous material or not. If it contains a hazardous material, it will be treated with the suitable hazardous material treatment. The strategy used in this case is the “treat as hazardous material” strategy. If it does not contain any hazardous material, it will be sorted whether it is recyclable or not. If it is recyclable, it will be recycled. In this case, the strategy is the “recycle” strategy. The recycled material from recyclable parts is inspected and stored before it is used as a recycled material in the remanufacturing process. If the part is not recyclable, it will be inspected whether it has high calorific capacity or not. The high calorific capacity part will be incinerated to provide energy for the remanufacturing process. The strategy for this case is the “incinerate” strategy. If its calorific capacity is not high, then the “landfill” strategy will be used to landfill the part.

3.5 METHODOLOGY FOR ESTIMATING THE LIFE CYCLE COST OF DIFFERENT PRODUCT STRUCTURES

The existing systems require extensive time and effort to estimate the life cycle cost of different structures of different product families. This section describes how to reduce the updating time and effort in accommodating different structures of different product families.

Based on the literature, different products can be developed based on a different product architectures approach. Product architecture is how the functional elements of a product are arranged into physical units and how these units interact with each other (Ulrich & Eppinger, 2008). Product architecture can be categorised into integrated and modular. In the modular architecture, each physical element of a product is mapped one-to-one to the functional element (Ulrich & Eppinger, 2008). By using this approach, various physical elements (modules and/or parts) can be combined easily to construct a variety of product.

This research takes into account different structures of different product families based on the modular product architecture approach. Different structures of different products are constructed by combining different assembled components or by combining the same components with different assembly sequences. By using this method, less amount of database is required compared to other existing systems because the information that needs to be stored is only the component information. It is not required to store complete information for each product platform, variant, and product variant. The information related to a product can be generated by combining information related to its assembled components and the assembly sequence. The information related to a product variant can be generated by combining information related to its product platform and variant. As a result, it will require less amount of time to develop the required database. In addition, it will be also easy to update the database. If a new product structure requires one or more new components, the new component can be updated by storing only the component information and then it can be selected as the assembled component of the new product structure.

To estimate the cost of different structures of different product families, this research proposes a method based on the modular product architecture approach explained above. By using the proposed method, the life cycle cost of each component level of a product family can be calculated, as shown in Figure 3.6. The life cycle cost of a certain component level of a product family can be calculated by summing all of its activity costs, the cost of its lower component level, and other costs consumed by each component level. First, the cost of a part is calculated by summing the part activities cost, the material cost, and the storage cost. The cost of a product platform is the summation of the product platform activities cost, the parts cost, the outsourced components cost, and the storage cost. The cost of a product variant is calculated by summing the product variant activities cost, the product platform cost, the parts of variant cost, the outsourced components of variant cost, and the storage cost. Last, the cost of a variant is the subtraction of the cost of the product variant and the cost of the product platform. It is not required to repeatedly calculate the life cycle cost of each component level in order to calculate the life cycle cost of different product families. Therefore, the cost estimation of different structures of different product families can be done with less time and effort used to calculate it.

The method of the life cycle cost estimation system, which is used to estimate the life cycle cost of different structures of different product families, is described further in Section 4.4 and Section 4.10.

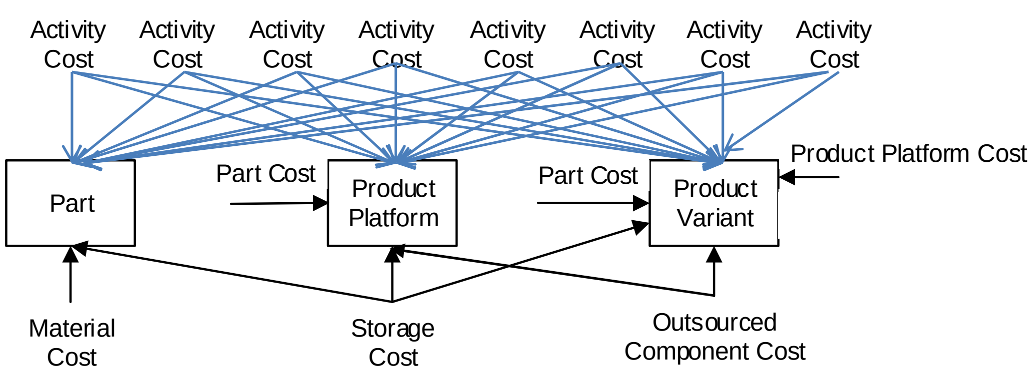

Figure 3.6. Life Cycle Cost Estimation Method for Different Structures of Product Family

3.6 METHODOLOGY FOR GENERATING ACTIVITY AND RESOURCE INFORMATION

As explained in Section 3.3, it is difficult to implement the time-driven activity based costing technique to estimate the life cycle cost at the early stage of product development. Therefore, this research attempts to integrate the time-driven activity-based costing technique with another system that can generate the required information. Section 3.6.1 outlines the types of a knowledge-based system that are proposed to transform the conceptual and not detailed information at the early stage of product development into the required information in estimating the life cycle cost using time-driven activity-based costing. Then, Section 3.6.2 explains how the knowledge-based system is designed. The implementation of the knowledge-based system is described in more detail in Section 4.3 to 4.9.

3.6.1 Knowledge Based System

In order to estimate the life cycle cost of a product family by using a time-driven activity-based costing technique, the market segment, the production volume, the product family structure, and the product family function must be transformed into the activities and the resources consumed by the product family. As described in Section 3.5, this research proposes that different structures of different products are constructed by combining different assembled components or by combining the same components with different assembly sequences. Therefore, two stages are proposed in this research to transform these attributes at the early stage of product development into the activities and resources consumed by the product family. First, these attributes are used to determine various components with their attributes of each component level of the product family. Second, information related to a component with its attributes and the product structure is transformed into the activities and resources consumed by the component of each component level of the product family. After that, the activity and resource information are used to calculate the life cycle cost of each component level of the product family by using the time-driven activity-based costing technique.

In this research, a knowledge-based system is proposed to transform the conceptual and not detailed information at the early stage of product development into the required information in estimating the life cycle cost using time-driven activity-based costing. A knowledge-based system is one of artificial intelligence computing tools that are designed to imitate the work of experts in specific areas of knowledge to solve a problem. It has already been implemented in various studies to generate the required information based on the available information at the early stage of product development.

There is no widely accepted definition of a knowledge-based system. The term “knowledge based system” is often used interchangeably with “expert system”. This research distinguishes between the definitions of knowledge-based system and expert system as suggested by Kendal and Creen (2007) and Hopgood (2012). Kendal and Creen (2007) state that “knowledge-based systems are computer programs that are designed to emulate the work of experts in specific areas of knowledge”. They divide the type of the knowledge-based system into seven categories, which are expert systems, neural networks, case-based reasoning, genetic algorithms, intelligent agents, data mining, and intelligent tutoring systems. According to Hopgood (2012), a knowledge-based system is one of the Artificial Intelligence computing tools, which include expert and rule-based systems, frame-based systems, intelligent agents, and case-based reasoning. Hopgood (2012) categorises neural networks, genetic algorithms, and other optimisation algorithms not as the type of knowledge based system, but as the type of computational intelligence.

Following the definition above, this research defines that an expert system is one type of knowledge-based system. An expert system can be used to imitate the decision-making process of humans and represents expertise in a particular specialised domain in order to solve a problem (Hopgood, 2012; Kendal & Creen, 2007). A rule-based expert system is an expert system that uses a set or sets of rules to represent knowledge. It could generate fast and consistent results and provide explanation capabilities. However, it can only be used in a specific domain, is difficult to adapt to changing environments, requires a lot of effort in development and maintenance, and cannot apply common sense and creativity.

A frame-based system uses frames as a means to represent and organise knowledge. Frames consist of slots that describe the object represented by the frame and facets that describe some knowledge or procedures about the attributes in the slots (Turban & Frenzel, 1992). In a frame-based system, empty slots should be filled with data and then rules or hierarchical reasoning can be used to solve a problem. This research categorises a frame-based system as a type of expert system.

An intelligent agent is an entity that can handle a specific task but it can make some decision on its own (Hopgood, 2012; Kendal & Creen, 2007). It perceives its environment, interacts with its environment, and reacts to changes in the environment autonomously and intelligently. This research does not need a system that can perceive and interact with its environment. For that reason, this research does not use an intelligent agent to generate the activities and resources information.

A case-based reasoning system imitates how humans solve a problem based on the past cases (Hopgood, 2012; Kendal & Creen, 2007). It uses similarity to find similar cases from past experiences and analogy to find solutions for similar cases. It can incorporate learning and reduce the amount of acquired knowledge, reduce the maintenance and development efforts, and can be easily extended to different domains. However, it does not provide clear explanation, requires care in storing cases, and requires efficient methods for accessing cases.

A neural network is a numerical learning technique that can be trained to classify, estimate, simulate and predict the process in generating measured data (Hopgood, 2012; Kendal & Creen, 2007). It works based on numerical data and requires large amounts of data to perform well. It is regarded as a black box that generates an output from a given input without any transparency. Similar to a neural network, a genetic algorithm is also one of the numerical techniques (Hopgood, 2012). A genetic algorithm is an optimisation algorithm which is designed to minimise a cost or maximise fitness. It does not work to improve a single trial solution, but a population of candidate solutions at the same time. As this research requires generating qualitative information related to activities and resources, neural networks and genetic algorithms cannot be used to generate the information required in this research.

Based on the review, the potential types of knowledge-based system that could be implemented to generate qualitative information related to activities and resources in this research are an expert system and a case-based reasoning. An expert system is generally suitable to solve a problem when the required expertise is available and does not change over time, the domain is in a manageable size, and the solution depends on logical reasoning. On the other hand, a case-based reasoning system can be used where the problem cannot be easily decomposed, the problem is less understood, available information is incomplete and it is dynamic. For that reason, an adapted case-based reasoning system is proposed in this research to generate various components with their attributes of each component level of a product family. Then, an expert system is proposed to generate the activities and resources consumed by each component level of the product family.

3.6.2 Design of the Knowledge-Based System

Three important elements are required in designing a knowledge-based system (Durkin, 1994; Kendal & Creen, 2007; Turban & Frenzel, 1992). The first element is a knowledge acquisition to acquire the knowledge. Then, a knowledge representation must be done to formalise and organise the knowledge in a certain form. Third, a reasoning structure as an inference engine must be built to provide the solutions based on the knowledge for each input. As the transformation in this research is conducted by using a knowledge-based system, those three elements are employed in this research.

To acquire the knowledge, five steps are carried out, which are the exploration of various modules, sub modules, and components that can satisfy the product family function, the exploration of manufacturing processes required to manufacture each component, the exploration of assembly methods and joining processes required to assemble the components into a product, the exploration of end of life processes required to recover the product, the exploration of outsourcing processes to procure the component and material, and the exploration of activities and resources consumed by the component and product at each of the product life cycle stages.

In the knowledge representation, the acquired knowledge is encoded to make it accessible to the knowledge-based system. There are various methods to represent the knowledge, which are the object-attributes-values, the scripts, the lists and trees, the rules, the semantic networks, the frames, the cases, and the logic (Durkin, 1994; Giarratano & Riley, 1994; Kendal & Creen, 2007; Turban & Frenzel, 1992). In this research, the rules are used to represent the knowledge in an expert system. For the case-based reasoning, the cases are used to represent the knowledge.

Last, this research builds six reasoning structures. The first reasoning structure is built to transform the product family function into modules and its sub modules that can satisfy the function. The generated information is used to retrieve the information related to the components with their attributes. The second reasoning structure uses the information related to the components with their attributes to determine the sequence of manufacturing process for each component. The next reasoning structure transforms the information related to product structure into the assembly method and joining process for each product. The fourth reasoning structure uses the attributes of the component, the assembly method, and the joining process of the product to determine the end of life strategy for each sub module. The fifth reasoning structure uses the component and its attributes information to generate the outsourcing process. Then, the last reasoning structure generates the information related to all activities and resources based on the sequence of manufacturing process, the assembly method, the joining process, the outsourcing process, and the end of life strategy.

3.7 METHODOLOGY FOR EVALUATING THE PROPOSED SYSTEM

This section describes how the proposed time-driven life cycle cost estimation system is evaluated. As this research is non-experimental type of research and the innovations of this research are in the form of tool or method, a qualitative validation is feasible to be conducted to evaluate the proposed system. Therefore, the purpose of the evaluation process in this research is only to conduct a qualitative validation. The evaluation process will not be conducted to verify the proposed system. The IEEE defines that the purpose of the validation of a system is to determine whether it satisfies specified requirements (2012). Referring to this definition, the evaluation process is used to determine whether the proposed system fulfils its objectives or not.

Section 3.7.1 describes about how the qualitative validation is conducted to evaluate the proposed system. In order to evaluate the proposed system, how to develop the prototype of the proposed system is explained in Section 3.7.2. Finally, how to collect the required data to evaluate the proposed system is presented in Section 3.7.3.

3.7.1 Evaluation Process

Various types of validation are proposed in the literature (Barth, Caillaud, & Rose, 2011). At this stage, it is not possible to validate the proposed system by comparing the results of this system to the results from other case studies in the past because none of the existing research provides the sufficient data for conducting the comparison. However, it is possible to conduct the validation process by applying the proposed system. Therefore, this research refers to the evaluation method proposed by Blessing and Chakrabarti (2009) to evaluate the proposed system as a design support. In their book, they proposed two types of evaluations, which are application evaluation and success evaluation. The similar evaluation method has been also implemented by Park (2005) and Wyatt, et al. (2012). The aim of the application evaluation is to assess the applicability and usability of the design support against the aim and objectives of the design support. The application evaluation assesses the outcomes that should be affected directly. On the other hand, the aim of the success evaluation is to assess the usefulness of the design support. This evaluation assesses the outcomes that are not directly addressed by the design support but are expected to be ultimately affected.

In this research, first, the application evaluation is performed by conducting a case study. The case study is conducted by estimating the life cycle cost of two different product families. The aim of the evaluation is to find out whether the proposed system can be used to generate activities and resources consumed by the part, product platform, variant, and product variant of the product families and whether the proposed system is able to

1. allocate and then calculate the life cycle cost of each component level of a product family
2. be easily adapted for different technologies and approaches
3. determine the end of life strategy for each sub module of a product family
4. integrate the end of life strategy into the life cycle cost model in order to estimate the life cycle cost of a product family
5. take into account different structures of different product families and estimate their life cycle cost with less time and effort
6. transform the market segment, the production volume, the product family structure, and the product family function into the required activities and resources information.

Second, the success evaluation is performed to assess the usefulness of the proposed system in evaluating a product family design. As the success evaluation assesses the outcomes that are not directly addressed by the system, the flexibility, effectiveness, accuracy, and transparency indicators are used to validate the usefulness of the system. A representative, who must be one of the senior management team of the collaborating company, is asked to indicate his/her ‘level of confidence’ in the flexibility, effectiveness, transparency, and accuracy of the proposed system and then give his/her feedback about the proposed system. The flexibility of the proposed system is evaluated as to whether it can be used to estimate the life cycle cost of various product families and their product variants in the collaborating company. The ability to generate the required information in order to estimate the cost of various product families at the early stage of product development is used to evaluate the effectiveness of the proposed system. The proposed system is considered transparent if it could estimate the critical costs of the product families and their product variants in order to perform a design evaluation. In this case, the proposed system must be able to estimate the life cycle cost of each component level of a product family. Finally, the accuracy of the proposed system is evaluated based on its ability in estimating the cost of the product families and their product variants in an acceptable accuracy for design evaluation purpose.

Chapter 6 explains further how the application evaluation and the success evaluation are conducted to evaluate the proposed system.

3.7.2 Prototype Development

In order to conduct the case study, a prototype of the proposed system is developed. Three main tools might be used to build the prototype, which are programming languages, shells, or development environments (Giarratano & Riley, 1994; Kendal & Creen, 2007; Turban & Frenzel, 1992). For that reason, the first step is to explore and learn about the tool that can be used to build the cost estimation system prototype. The programming languages are not specifically designed to build the knowledge-based system. They provide most flexibility but require the longest time in building the prototype. The shells can be used to build the prototype without having to build the entire system. They contain the basic components of expert systems without the domain specific knowledge. By using the shells, the prototype can be built by only adding the knowledge component. As a result, the use of shells will reduce the time and labour in building the prototype. Finally, the development environments provide less flexibility than programming languages but they take less time to build the prototype.

The system implements both the expert system and the adapted case-based reasoning system to estimate the life cycle cost of a product family. In addition the system also requires integrating the time-driven activity-based costing technique and the knowledge-based system. Therefore, this research uses a programming language as the development tool to build the prototype, to ensure that the integration between the time-driven life cycle cost estimation technique and the knowledge-based system can be performed.

The design and the prototyping process of the proposed system are explained further in Chapter 5.

3.7.3 Data Collection

This system is applicable for various types of discrete product family. Therefore, the full application of this system requires abundant data. To keep this research manageable, the collected data is limited to the required data to conduct the case study. The case study requires several data that could be collected by using various techniques. The data related to the developed product families, the product variants of each product family, the sub modules of each product variant, the component of each sub module, and the component supplier are collected from the archival records of the collaborating company.

As some data are unavailable and confidential, literature review is used as a method to acquire the unavailable and confidential data. The purpose of this system is to assist in evaluating a product family design by estimating the life cycle cost. It is not used for accounting purposes. In addition, the aim of the case study is only to show that the proposed system is able to fulfil its objective. For that reason, a literature review is acceptable to be used as a method to acquire the data.

This research uses various available patent documents, mechanism handbooks, and bill of material documents to acquire the knowledge about various modules with their sub modules and component that can satisfy the function. As a lot of modules, sub modules, and components are available in the market, this research limits the exploration to the module, sub module, and component that can satisfy the functions of the product selected for the case study. Design for manufacturing and assembly handbooks are used as a guideline to select the manufacturing process, assembly method, and joining process (Boothroyd, et al., 2011). To select the end of life process, end of life directives and end of life articles are used as a guideline.

The information related to activities consumed by components and products and the resources consumed by the activities is acquired by conducting an analysis of organisation structure and identification of the process activities. First, the process flow is studied and defined in terms of major activities. Then the activities are embedded into the resource groups or in this case the departments to identify the resources consumed by each activity. Various manufacturing process handbooks are used to explore and investigate the process and define the activity. End of life directives and end of life articles are used to determine the end of life processes and define their activities. The handbooks, directives, and articles also are used to identify the driver of each activity and its usage.

3.8 SCOPE AND LIMITATION OF THE RESEARCH

This research develops a prototype to evaluate the proposed life cycle cost estimation system. The development of the system prototype is out of the scope of this research. Therefore, the development process of the system prototype is not discussed in detail in this research.

The proposed system is applicable to estimate the life cycle cost of different discreet manufactured product families. A discrete product family consists of two or more manufactured products that are assembled from more than one component. The component itself is manufactured by using one or more manufacturing processes that can be performed discontinuously.

At this stage, there is not enough data available for verifying the proposed life cycle cost estimation system. The collaborating company cannot provide some of the required data because of confidentiality concerns. In addition, none of the existing research provides sufficient data for conducting the system verification. Therefore, the purpose of the evaluation process is only to conduct a qualitative validation. The evaluation process will not be conducted to verify the proposed system.

The full application of this system requires abundant data. To keep this research manageable, the collected data is limited to that required to conduct the case study. Some data are collected from the archival records of the collaborating company. The unavailable and confidential data are assumed, based on literature. The assumptions for the unavailable and confidential data are considered to be able to represent reality.

This research uses only two product families as the case study in order to illustrate and evaluate the proposed life cycle cost estimation system. The life cycle cost estimation of two product families is sufficient to evaluate the applicability of the proposed system. Even though the case study takes two product families of a certain product as the examples, the proposed system can undoubtedly be used in other domains.

Chapter 4: Time-driven Life Cycle Cost Estimation System

In order to solve the difficulties in estimating the life cycle cost of a product family at the early stage of product development, this research proposes a product family design support system called a time-driven life cycle cost estimation system. The system is called a time-driven life cycle cost estimation system because it estimates the life cycle cost of a product family based on the consumption of time to conduct the activity required by the component level of the product family. The system is developed based on the proposed methodologies in Chapter 3.

In the first section of this chapter, the framework of the proposed system is presented. As the proposed system consists of three main parts, the framework describes all three parts of the system. Each part of the proposed system consists of several steps. Therefore, the steps of each part of the system are explained in Sections 4.2 to 4.10.

Section 4.2 and Section 4.3 describe the steps of the first part of the system. This part transforms the function required by a product family into information related to the components and their attributes of the product family. Section 4.2 explains how to define a product family and its attributes. Then, Section 4.3 presents the process to generate various components and their attributes that can carry out the sub function of the product family.

Then, the second part of the system, as presented in Sections 4.4 to 4.9, generates all activities and resources consumed by the product family, based on the information generated in the first part of the system. Section 4.4 describes how to define the structure of the product family. It is followed by the generation of the assembly process sequence of the product family in Section 4.5. Then, the generation process of end of life strategy for each sub module of the product family is presented in Section 4.6. After that, Section 4.7 and Section 4.8 describe how the system generates the sequence of the manufacturing process to manufacture the in-house component and the outsourcing process for the outsourced component respectively. In Section 4.9, the information generated in Sections 4.4 to 4.8 is used to generate the activity and resource information for component, product platform, product variant, taken back product, recovered sub module, and recovered material.

Finally, the last part of the system described in Section 4.10 uses the information generated in the second part of the system to calculate the life cycle cost of each component level of the product family. Section 4.10 explains the process to calculate the rate of recovered material, recovered sub module, component, product platform, and product variant. In addition, the life cycle cost of each in house component, product platform, and product variant of the product family are also calculated.

In order to evaluate the proposed time-driven life cycle cost estimation system, a prototype of the proposed system is developed, as described in Chapter 5. Chapter 5 also gives an explanation of how the proposed system is implemented. In addition, Chapter 6 gives an example of the implementation of the proposed system to estimate the lifecycle cost of a product family.

4.1 TIME-DRIVEN LIFE CYCLE COST ESTIMATION FRAMEWORK

This section describes the framework of the proposed time-driven life cycle cost estimation system to solve the difficulties in estimating the life cycle cost of a product family at the early stage of product development. The framework of the proposed time-driven life cycle cost estimation system shown in Figure 4.1 is developed based on the methodologies explained in Chapter 3. The detail of the implementation of the proposed framework is explained in Sections 4.2 to 4.10.

Based on the literature review, a product family at the early stage of product development is characterised by its market segment, production volume, product structure, and product function attributes. To define various product families at the early stage of product development, these attributes need to be defined. In order to define different product families at the early stage of product development, the proposed time-driven life cycle cost estimation system requires the user to input the market segment, production volume, product structure, and product function of each product variant of the product family. By inputting these attributes, the proposed system is able to define different product families at the early stage of product development as long as they consist of two or more manufactured products that are assembled from more than one component.

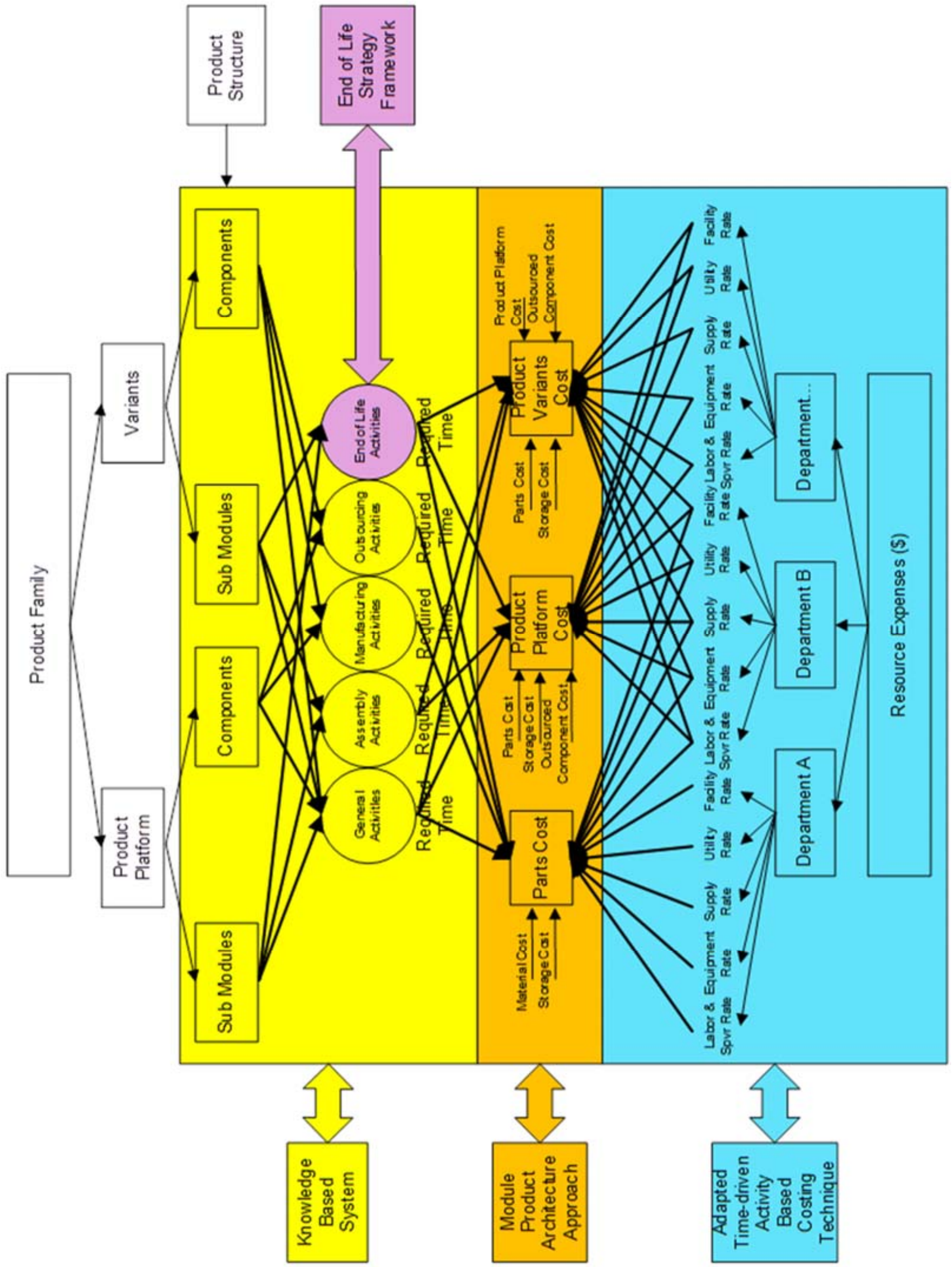

Figure 4.1. Time-driven Life Cycle Cost Estimation Framework

First, the user needs to define the product family that is developed. It includes the product family names, the product variants of each product family to satisfy customers from a certain market segment, percentage of the taken back product variant, and the production volume of each product variant in a year. Then, the user needs to select the required sub function, the preferred concept, the utilisation, and other specific factors of the product platform and the variants of each product family. Based on these inputs, the knowledge-based system will generate all sub modules and components of each product platform and variant.

Next, the user needs to define the product structure of each product variant by inputting the component assembly sequences, the assembled components, and the component assembly repetition for its product platform and variant. In addition, the user needs to select the assembly method and the joining process that will be implemented in conducting the assembly process.

After that, the end of life strategy of each sub module and its quantity will be generated based on the end of life strategy generation method. The end of life strategy will be used to generate the recovery processes required by each sub module. In addition, the knowledge-based system will generate other processes required by each sub module and component. Then, the knowledge-based system will generate the activities and the resources required by each sub module and component based on the generated processes. The knowledge-based system will also generate the required time to conduct each activity.

In order to allocate and then calculate the cost of each component level of a product family, the adapted time-driven activity-based costing technique is used to assign the resource expenses to each department and then calculate the rate of each department resource. The adapted time-driven activity-based costing technique is also used to calculate the cost of each activity based on the required time to conduct the activity. Then, the activity cost is categorised according to the cost component categories and the lifecycle stages.

Finally, the life cycle cost of a certain component level of a product family can be calculated based on the modular product architecture approach. The life cycle cost of a certain component level of a product family can be calculated by summing all of its activity costs, the cost of its lower component level, and other costs consumed by the component level. For example, the cost of a product platform is the summation of the product platform activities cost, the parts cost, the outsourced components cost, and the storage cost.

As explained in Section 3.6, two stages are proposed in this research to transform these attributes at the early stage of product development into the activities and resources consumed by the product family. First, these attributes are used to determine various components with their attributes of each component level of the product family. Second, information related to a component with its attributes and the product structure is transformed into the activities and resources consumed by the component of each component level of the product family. For that reason, the proposed system consists of three main parts as shown in Figure 4.2. The first part of the system generates all components and their attributes of the product family. Then, the second part of the system generates all activities and resources consumed by the product family. Finally, the last part of the system allocates and calculates the life cycle cost of each component level of the product family. Each part contains various databases, to be able to generate or calculate the information. Section 5.3 and Section 5.4 explain the development of these databases.

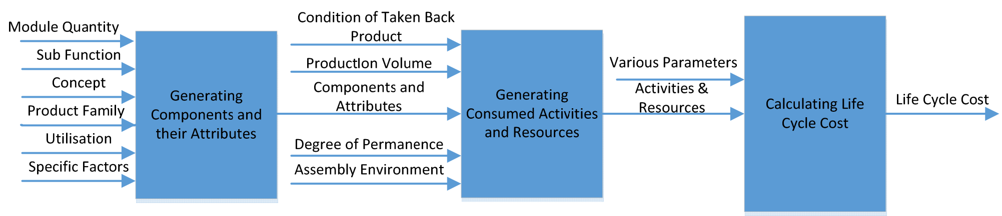

Figure 4.2. Time-driven Life Cycle Cost Estimation System

The first part of the proposed system allows the user to define the product family that is developed and then generates the components and their attributes of the product family. The first part of the system is described further by the framework shown in Figure 4.3. The steps to define a product family and the steps to generate various components and their attributes are explained in Section 4.2 and Section 4.3 respectively.

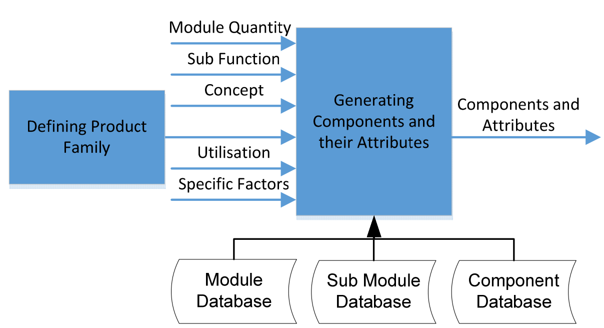

Figure 4.3. Framework to Generate Components and Their Attributes

The aim of the second part of the system is to generate activities and resources consumed by the product family. The consumed activities and resources are influenced by the processes required by the product family. A product family requires various processes from the design stage until the end of life stage. The assembly process, the recovery process, the manufacturing process, and the outsourcing process are influenced by the attributes of the product family as explained in Section 2.3. For that reason, the second part of the system is used to generate these processes and then generate all activities and resources consumed by the product family. As shown in Figure 4.4, the second part of the system consists of six steps. The first step defines the structure of the product family. Then, the second step generates the assembly process sequence to assemble the generated components into the product family. The end of life strategy for the taken back product is generated in the third step of this framework. After that, the next step generates the sequence of manufacturing process or the manufacturing process chain to manufacture the in-house component of the product family. It is followed by the generation of outsourcing process of outsourced material and component. Last, the generated information is used to generate all activities and resources consumed by the product family. The detailed explanations of the steps of this framework are presented in Section 4.4 to Section 4.9.

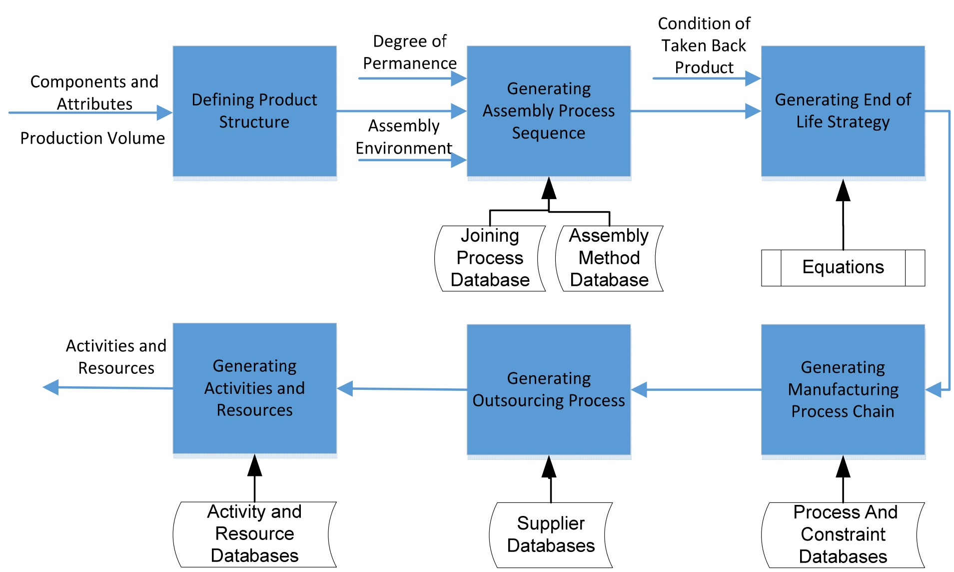

Figure 4.4. Framework to Generate Activities and Resources

The last part of the system allocates and calculates the life cycle cost of each component level of the product family. The framework to allocate and calculate the life cycle cost of each component level of the product family is presented in Figure 4.5. First, the system calculates the cost of each weight or the rate of recovered material. The rate of the recovered material is used to calculate the rate of an in-house component. Then, the cost of each unit or the rate of all the recovered sub modules is calculated. The rate of the recovered sub module, the rate of outsourced component, and the rate of the in-house component are used to calculate the rate of a product platform. The rate of a product variant is calculated by summing the rate of the product platform, the rate of recovered sub module, the rate of the outsourced component, the rate of the in-house component and other relevant rates. Finally, the calculated rates are used to calculate the life cycle cost of each component level of the product family. The detail of all steps in calculating the life cycle cost of each component level of the product family is described in Section 4.10.

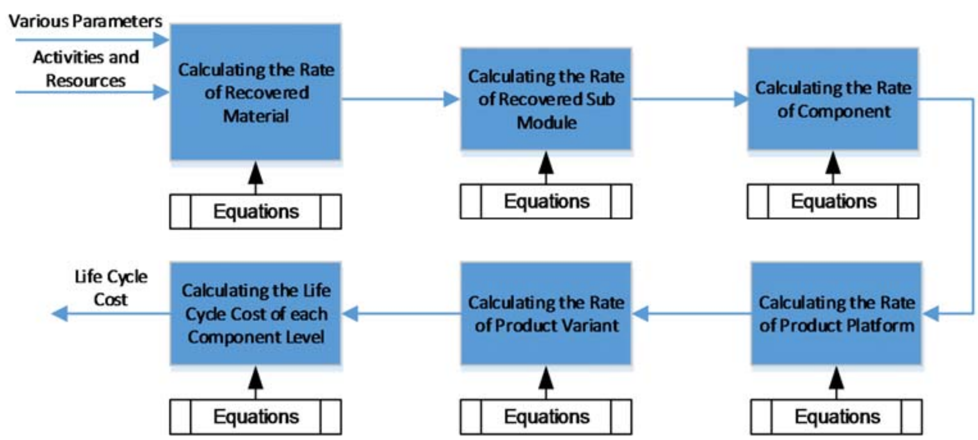

Figure 4.5. Framework to Calculate Life Cycle Cost

4.2 DEFINING PRODUCT FAMILY

In the first step of the first part, one or more product families, which are going to be developed to meet the needs of a certain market segments, need to be defined. The inputs of this step are the product families, the product variants of each product family, percentage of the taken back product variant, and the production volume of each product variant in a year.

Then, the system will calculate the quantity of production runs and the quantity of product orders for each product variant and each product platform. The quantity of production runs and the quantity of product orders are used to calculate the life cycle cost in Section 4.10. The percentage of the taken back product variant will be used to calculate the quantity of the recovered sub module, as described in Section 4.6.

The quantity of production runs is the quantity of productions days required to produce the production volume in a year. To calculate the quantity of production runs, the production volume is divided by the production capacity as shown in Equation 4.1. The production capacity is the quantity of products that can be produced in one day by using current available resources. The production capacity is determined based on the capacity of a company to produce the product.

$$\boldsymbol{QPR = \frac{PV}{PC}} \qquad \text{Equation 4.1}$$

The quantity of product orders is how many times a product is ordered to a production floor in a year. The product order is mostly placed and received every week. For that reason, the quantity of product orders is calculated by dividing the quantity of production runs with the working days in a week as shown in Equation 4.2. The quantity of product orders will determine how many times the production planning and procurement must be conducted in a year.

$$\boldsymbol{QPO = \frac{QPR}{WD}} \qquad \text{Equation 4.2}$$

4.3 GENERATING COMPONENT AND ITS ATTRIBUTES

Each product variant has several required sub functions that must meet the needs of its certain market segment. This step transforms each required sub function of the product variant into one or more components that can be used to carry out the sub function. As a product variant is a combination of a product platform and a variant, this step is conducted for the product platform and the variant. The transformation of the sub function of the product platform is conducted once for each product family. The transformation of the sub function of the variant is conducted for each product variant of the product family.

The sub function of the product variant can be carried out by using various types of modules. A module is a combination of subassemblies and/or parts of a product variant that is designed to carry out at least one sub function of the product variant. Each module consists of one or more standardised and interchangeable sub modules that can be independently produced or purchased in the market. Various sub module options are available in the market for each sub module. However, only one option for each sub module can be selected to carry out the required sub function. The selected sub module option could be a part type or a sub assembly type of sub module. The part type of sub module option consists of only one component. If the sub module option is a sub assembly type of sub module, it consists of more than one component. Therefore, three steps are proposed in this research to generate the components of the product variant, as shown in Figure 4.6.

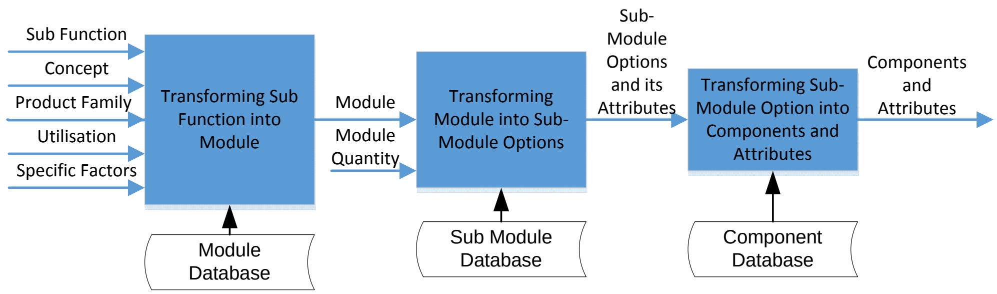

Figure 4.6. Generating Component and Attributes

First, the required sub function is transformed into a module. The module is selected by considering the preferred concept, the utilisation, and other specific factors of the product variant. A preferred concept is a concept of solution that is preferred to be used in carrying out the sub function. A utilisation is the common implementation of the module in various market segments. Therefore, the inputs of this step are the required sub functions, the preferred concept, the utilisation, and the specific factors of the product variant. The inputs are used to search and generate the module from the module database of the system. An adapted case-based reasoning system is implemented to search the most similar module to the requirement. The sub function, the concept, the utilisation, and the specific factors are inputted sequentially to search the most similar module. If the module is not available in the database, a new module can be added to the database with its function, concept, utilisation, and specific factors. After the system generates the module that can carry out the required sub function, the required quantity of the module for each product variant must be inputted to the system. This step is used to structure the module and narrow the sub module options down before continuing to the next step.

Next, the module is transformed into its sub module options with their own quantities, types, and procurement strategies. The sub module for each module is generated based on the sub module database of the system. The quantity and the procurement strategy of each sub module are also generated based on the sub module database. The procurement strategy is how the sub module will be procured. There are two procurement strategies, which are in-house and outsourced strategies. In-house sub module means that the sub module is manufactured independently in the company. On the other hand, if the sub module is bought from a third party, it is called an outsourced sub module.

Finally, each sub module option is transformed into its components and their attributes. The generated component and its attributes will influence the end of life, the assembly, the manufacturing, and the procuring process. In this step, the sub module option is transformed into its components based on the component database of the system. The part type of sub module option is transformed into one component. The sub assembly type of sub module option is transformed into more than one component. The database also provides the quantity, the procurement strategy, the material, the weight, the thickness, and the envelope size of the component for each component. The envelope size of the component is the diameter, the length, the width, and the height of a box or a cylinder that can contain the component. Based on the generated attributes, the system calculates the storage volume of each component and sub module option. Both storage volumes are used to calculate the life cycle cost later in Section 4.10.

Some component of the in-house sub module option could be manufactured in-house or purchased from a third party. For the in-house component, the system generates several additional attributes, which are the basic shape, the shape complexity, the required size tolerance, the required surface roughness, the required material property, the required surface finish, manufacturing complexity coefficient, and the additional feature. The basic shape, the shape complexity, and the additional feature are described further in Section 4.7.1 and 4.7.2. The manufacturing complexity coefficient is a coefficient that determines the difficulty of the process to manufacture the in-house component. The higher the coefficient means that the process requires more time. The manufacturing complexity coefficient is defined to adjust the required time of manufacturing process activities for each in-house component as shown in Section 4.9.

If the in-house component has any additional features, then the system also generates several additional attributes for the additional feature, which are the name, the type, the quantity, the envelope size, the required size tolerance, the required surface roughness, and the required surface finish of the additional feature.

4.4 DEFINING PRODUCT STRUCTURE

After all components of each product variant are generated, the structure of each product variant can be defined (Du, et al., 2001; Jiao & Tseng, 2000; Park & Simpson, 2005; Weustink, et al., 2000). The structure of the product variant is derived from the structure of its product family. The product structure defines how the functions or components of a product are arranged in a hierarchical structure. In this step, the structure of the product variant is defined by inputting the component assembly sequences, the assembled components, and the component assembly repetition for the product platform and the variant of the product variant. The product structure definition for the product platform is conducted once for each product family. The product structure definition for the variant is conducted for each product variant of the product family. The defined product structure will influence the assembly process sequence to assemble each component of the product family. It also will be used to calculate the life cycle cost in Section 4.10.

Various methods have been proposed to represent the assembly sequence and its assembled components of a product family such as assembly list, directed graph, liaison diagram, AND/OR graph, assembly matrix, undirected graph, unified modelling language and hybrid methods (AlGeddawy & ElMaraghy, 2013; Chen et al., 2006; De Lit, Danloy, Delchambre, & Henrioud, 2003; Du, et al., 2001; Gupta & Krishnan, 1998; Jiao & Tseng, 1999b; Liu, Wong, & Lee, 2010; Park & Simpson, 2005; Zhang, Jiao, & Helo, 2006). In this research, the assembly list is used to represent the assembly sequence and the assembled components of all product variants of the product family, because it is the simplest method and easiest way to represent them.

4.5 GENERATING ASSEMBLY PROCESS SEQUENCE

Assembly process is a process that can be used to pick, orient, insert, place, and join the components of a product in a sequence by using a certain joining process and assembly method. To assemble a product variant, all components of the product variant are assembled according to its product structure. In this step, the material of the component, the thickness of the component, the joining production volume, the required degree of permanence of each assembly sequence, the number of product variants, the production volume of all product variants, and the assembly environment of each product variant are used as the inputs (Boothroyd, et al., 2011; Swift & Booker, 2003). In addition, the product structure of the product variant is added to the inputs. The outputs of this step are the joining process and the assembly method of each component assembly sequence that can be used to pick, orient, insert, place, and join the assembled components into a sub-assembly. The joining process and assembly method for each assembly sequence will influence the assembly and disassembly activity and the resource consumed by the product family.

The generation of the viable assembly processes are conducted for product platform and for variant. The generation process for the product platform is conducted once for each product family. On the other hand, the generation process for the variant is conducted for each product variant of the product family. The generation of the assembly process is shown in Figure 4.7.

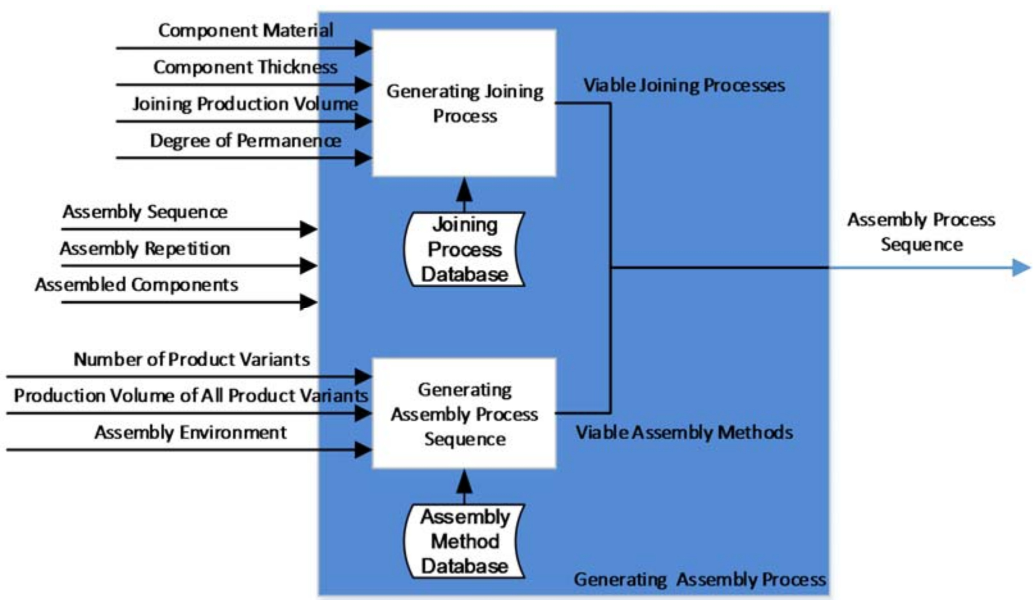

Figure 4.7. Generating Assembly Process Sequence

The joining process is a process that can be used to join more than one component into a sub-assembly. The joined components could have the same or different materials. Various joining processes are available in the market. In this research, the joining processes are categorised into permanent, semi-permanent, and non-permanent joining processes. This categorisation is used to generate all viable joining processes to join the assembled components of each component assembly sequence.

The viable joining processes to assemble the assembled components of each component assembly sequence are generated based on the material of the components, the smallest component thickness, the joining production volume, and the required degree of permanence for the assembly sequence (Swift & Booker, 2003). The assembled components could have different materials. For that reason, there are some joining processes that can be used to assemble two components with different materials. The joining production volume is calculated by multiplying the component assembly repetition defined in the previous section with the production volume of the product variant or the product platform defined in Section 4.2. The equations to calculate the joining production volume of the product variant or the product platform are shown in Equation 4.3 and Equation 4.4 respectively. The degree of permanence types for the assembly sequence could be permanent, semi-permanent, or non-permanent degree of permanence type.

$$\boldsymbol{JPVPV = AR \times PV} \qquad \text{Equation 4.3}$$

$$\boldsymbol{JPVPP = AR \times \sum_{Product\ Variant\ in\ the\ same\ Product\ Family} PV} \qquad \text{Equation 4.4}$$

The outputs of this step are all viable joining processes to assemble the assembled components of each component assembly sequence. Then, the viable joining processes are used to generate the assembly process sequence.

The assembly method is a method that can be used to pick, orient, insert, and place a component before it is joined with another component. In this research, three assembly method categorisations are used, which are manual, flexible, and dedicated (Boothroyd, et al., 2011; Swift & Booker, 2003). By using the manual assembly method, the assembly process is conducted manually by an operator by using simple and less expensive equipment. The flexible assembly method uses equipment that can modify the assembly process easily. The dedicated assembly method is characterised by the use of special purpose equipment to assemble a specific product.

To generate the assembly methods, the required inputs are the number of all product variants, the production volume of all product variants, and the assembly environment of each product variant. The number of all product variants and the production volume of all product variants are calculated by the system. The number of all product variants is calculated by counting all product variants. The production volume of all product variants is calculated by summing the production volume of all product variants as shown in Equation 4.5. On the other hand, the assembly environment is inputted manually for each component assembly sequence. The assembly environment of the product variant could be a non-hazardous or a hazardous environment. If the assembly sequence requires a sterile or clean environment, then it will be considered requiring a hazardous environment.

$$\boldsymbol{PVAPV} = \sum_{\boldsymbol{Product\,Variant}} \boldsymbol{PV} \qquad \text{Equation 4.5}$$

The outputs of this step are the assembly methods to pick, orient, insert, and place a component before it is joined with another component. The assembly methods could be manual, flexible, or dedicated assembly methods. Then, the assembly methods are used to generate the assembly process sequence.

An assembly process sequence consists of the assembly sequence, the assembled components, the component assembly repetition, the joining process, the assembly method, and the assembly/disassembly complexity coefficient. The assembly/disassembly complexity coefficient is a coefficient that determines the difficulty of the process to bring together the assembled components. The assembly/disassembly complexity coefficient is defined to adjust the required time of the assembly process and disassembly process activities for each component assembly sequence, as shown in Section 4.9. In this step, the assembly process sequence is generated for the product platform and for the variants of the product family. The component assembly sequence, its assembled components, and its repetition are generated from the defined product structure. Then, the generated assembly methods, the selected joining processes, and the assembly/disassembly complexity coefficient are added to generate the assembly process sequence.

4.6 GENERATING END OF LIFE STRATEGY

The steps to generate the end of life strategy are shown in Figure 4.8. First, the proposed system uses the procurement strategy and the degree of permanence as the factors to determine the end of life strategy for the sub assembly type of sub module. Then, the system used the same factors to determine the end of life strategy for the part type of sub module. Then, the end of life strategy for recovered material is determined based on the material type of the recovered material. The proposed system generates the end of life strategy based on the end of life determination method, explained in Section 3.4

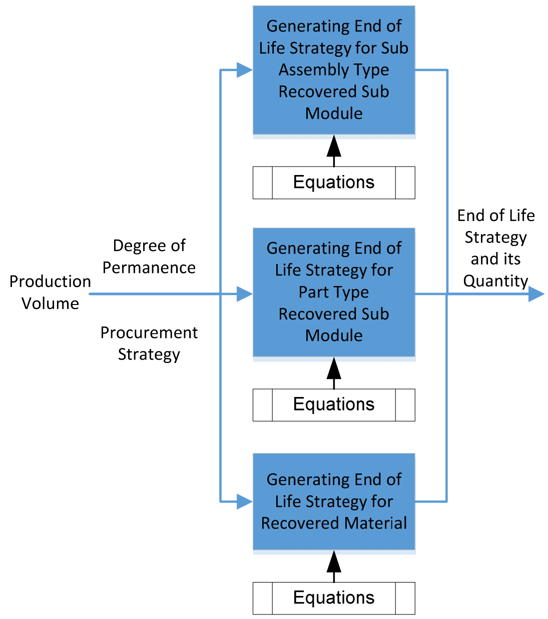

Figure 4.8. Generating End of Life Strategy

After that, the quantity of each end of life strategy is calculated by using several equations derived from the framework shown in Figure 3.5 based on the end of life conditions and the production volume of the sub module. The estimated end of life conditions of the sub module consist of whether the sub module is working or not, has wear/tear or not, is repairable or not, and is recondition able or not. The term working in this case means that the sub module is functioning, safe, and complies with the available standard/direction. The end of life strategy and its quantity will influence the activity and resource consumed by a product family at the end of life stage.

The quantity of the recovered sub module for each end of life strategy can be calculated by inputting the estimated percentage of taken back product of production volume, the estimated percentage condition of taken back product, and the estimated percentage of each conditions of its sub module. Various conditions of taken back product and its sub module that influence the quantity of the recovered sub module are shown in Table 4.1 below. The quantity of taken back product of each product variant can be calculated by multiplying the percentage of working product of taken back product with the production volume of the product variant as shown in Equation 4.6.

$$\boldsymbol{QTBP} = \boldsymbol{A}\% \times \boldsymbol{PV} \quad \text{Equation 4.6}$$

Table 4.1. Various Conditions of Taken Back Product and Its Sub Module

Various Conditions of Taken Back Product and Its Sub Module
Working Product of Taken Back Product
Working Sub Assembly of Non-Working Product
Tear/Wear Sub Assembly of Working Sub Assembly
Repairable Sub Assembly of Non-Working Sub Assembly
Repairable Permanent Joined Sub Assembly
Recondition able Tear/Wear Sub Assembly
Working Part of Taken Back Product
Tear/Wear Part of Working Part
Repairable Part of Non-Working Part
Repairable Permanent Joined Part
Recondition able Tear/Wear Part

The equations to calculate the recovered sub module quantity of each end of life strategy for non-
life strategy for non-permanently and permanently assembled in-house sub assemblies are listed in
assemblies are listed in Table 4.2 and

Table 4.3 respectively. Table 4.4 and Table 4.5 show the equations to calculate the recovered sub module quantity of each end of life strategy for non-permanently and permanently assembled outsourced sub assemblies.

Table 4.2. Equation of each End of Life Strategy for Non-Permanently Assembled In-house Sub Assembly

End of Life Strategy	**Recovered Sub Module Quantity**	**Equation No.**
Reuse as Sub Assembly	$\boldsymbol{QNIRS} = \sum_{\boldsymbol{product\ variant}}\big((\boldsymbol{1}-\boldsymbol{D}\%) \times (\boldsymbol{B}\% \times \boldsymbol{A}\% + \boldsymbol{C}\% \times (\boldsymbol{1}-\boldsymbol{B}\%) \times \boldsymbol{A}\%) \times \boldsymbol{PV} \times \sum_{\boldsymbol{module}}(\boldsymbol{QM} \times \boldsymbol{QSM})\big)$	Equation 4.7
Reuse as Sub Assembly with Recondition	$\boldsymbol{QNICS} = \sum_{\boldsymbol{product\ variant}}(\boldsymbol{G}\% \times \boldsymbol{D}\% \times (\boldsymbol{B}\% \times \boldsymbol{A}\% + \boldsymbol{C}\% \times (\boldsymbol{1}-\boldsymbol{B}\%) \times \boldsymbol{A}\%) \times \boldsymbol{PV} \times \sum_{\boldsymbol{module}}(\boldsymbol{QM} \times \boldsymbol{QSM}))$	Equation 4.8
Reuse as Sub Assembly with Repair	$\boldsymbol{QNIPS} = \sum_{\boldsymbol{product\ variant}}(\boldsymbol{E}\% \times (\boldsymbol{1}-\boldsymbol{C}\%) \times (\boldsymbol{1}-\boldsymbol{B}\%) \times \boldsymbol{A}\% \times \boldsymbol{PV} \times \sum_{\boldsymbol{module}}(\boldsymbol{QM} \times \boldsymbol{QSM}))$	Equation 4.9
Reuse as Sub Assembly with Replacement	$\boldsymbol{QNILS} = \sum_{\boldsymbol{product\ variant}}(((\boldsymbol{1}-\boldsymbol{E}\%) \times (\boldsymbol{1}-\boldsymbol{C}\%) \times (\boldsymbol{1}-\boldsymbol{B}\%) \times \boldsymbol{A}\% + (\boldsymbol{1}-\boldsymbol{G}\%) \times \boldsymbol{D}\% \times (\boldsymbol{B}\% \times \boldsymbol{A}\% + \boldsymbol{C}\% \times (\boldsymbol{1}-\boldsymbol{B}\%) \times \boldsymbol{A}\%)) \times \boldsymbol{PV} \times \sum_{\boldsymbol{module}}(\boldsymbol{QM} \times \boldsymbol{QSM}))$	Equation 4.10
Recovered Material	$\boldsymbol{QNIMS} = \sum_{\boldsymbol{product\ variant}}(((\boldsymbol{1}-\boldsymbol{E}\%) \times (\boldsymbol{1}-\boldsymbol{C}\%) \times (\boldsymbol{1}-\boldsymbol{B}\%) \times \boldsymbol{A}\% + (\boldsymbol{1}-\boldsymbol{G}\%) \times \boldsymbol{D}\% \times (\boldsymbol{B}\% \times \boldsymbol{A}\% + \boldsymbol{C}\% \times (\boldsymbol{1}-\boldsymbol{B}\%) \times \boldsymbol{A}\%)) \times \boldsymbol{PV} \times \sum_{\boldsymbol{module}}(\boldsymbol{QM} \times \boldsymbol{QSM}))$	Equation 4.11

Table 4.3. Equation of each End of Life Strategy for Permanently Assembled In-house Sub Assembly

End of Life Strategy	Recovered Sub Module Quantity	Equation No.
Reuse as Sub Assembly	$\boldsymbol{QPIRS = 0}$	-
Reuse as Sub Assembly with Recondition	$\boldsymbol{QPICS = 0}$	-
Reuse as Sub Assembly with Repair	$\boldsymbol{QPIPS} = \sum_{\boldsymbol{product\ variant}} (\boldsymbol{F}\% \times (\boldsymbol{B}\% \times \boldsymbol{A}\% + (\boldsymbol{1} - \boldsymbol{B}\%) \times \boldsymbol{A}\%) \times \boldsymbol{PV} \times \sum_{\boldsymbol{module}} (\boldsymbol{QM} \times \boldsymbol{QSM}))$	Equation 4.12
Reuse as Sub Assembly with Replacement	$\boldsymbol{QPILS} = \sum_{\boldsymbol{product\ variant}} ((\boldsymbol{1} - \boldsymbol{F}\%) \times (\boldsymbol{B}\% \times \boldsymbol{A}\% + (\boldsymbol{1} - \boldsymbol{B}\%) \times \boldsymbol{A}\%) \times \boldsymbol{PV} \times \sum_{\boldsymbol{module}} (\boldsymbol{QM} \times \boldsymbol{QSM}))$	Equation 4.13
Recovered Material	$\boldsymbol{QPIMS} = \sum_{\boldsymbol{product\ variant}} ((\boldsymbol{1} - \boldsymbol{F}\%) \times (\boldsymbol{B}\% \times \boldsymbol{A}\% + (\boldsymbol{1} - \boldsymbol{B}\%) \times \boldsymbol{A}\%) \times \boldsymbol{PV} \times \sum_{\boldsymbol{module}} (\boldsymbol{QM} \times \boldsymbol{QSM}))$	Equation 4.14

Table 4.4. Equation of each End of Life Strategy for Non-Permanently Assembled Outsourced Sub Assembly

End of Life Strategy	Recovered Sub Module Quantity	Equation No.
Reuse as Sub Assembly	$\boldsymbol{QNORS} = \sum_{\boldsymbol{product\ variant}} ((\boldsymbol{1} - \boldsymbol{D}\%) \times (\boldsymbol{B}\% \times \boldsymbol{A}\% + \boldsymbol{C}\% \times (\boldsymbol{1} - \boldsymbol{B}\%) \times \boldsymbol{A}\%) \times \boldsymbol{PV} \times \sum_{\boldsymbol{module}} (\boldsymbol{QM} \times \boldsymbol{QSM}))$	Equation 4.15
Reuse as Sub Assembly with Recondition	$\boldsymbol{QNOCS} = \sum_{\boldsymbol{product\ variant}} (\boldsymbol{G}\% \times \boldsymbol{D}\% \times (\boldsymbol{B}\% \times \boldsymbol{A}\% + \boldsymbol{C}\% \times (\boldsymbol{1} - \boldsymbol{B}\%) \times \boldsymbol{A}\%) \times \boldsymbol{PV} \times \sum_{\boldsymbol{module}} (\boldsymbol{QM} \times \boldsymbol{QSM}))$	Equation 4.16
Reuse as Sub Assembly with Repair	$\boldsymbol{QNOPS = 0}$	-
Reuse as Sub Assembly with Replacement	$\boldsymbol{QNOLS = 0}$	-
Recovered Material	$\boldsymbol{QNOMS} = \sum_{\boldsymbol{product\ variant}} ((\boldsymbol{1} - \boldsymbol{C}\%) \times (\boldsymbol{1} - \boldsymbol{B}\%) \times \boldsymbol{A}\% + (\boldsymbol{1} - \boldsymbol{G}\%) \times \boldsymbol{D}\% \times (\boldsymbol{B}\% \times \boldsymbol{A}\% + \boldsymbol{C}\% \times (\boldsymbol{1} - \boldsymbol{B}\%) \times \boldsymbol{A}\%)) \times \boldsymbol{PV} \times \sum_{\boldsymbol{module}} (\boldsymbol{QM} \times \boldsymbol{QSM}))$	Equation 4.17

The equations to calculate the recovered sub module quantity of each end of life strategy for non-permanently and permanently assembled in-house parts are listed in Table 4.6 and Table 4.7 respectively. Table 4.8 and Table 4.9 show the equations to calculate the recovered sub module quantity of each end of life strategy for non-permanently and permanently assembled outsourced parts.

Table 4.5. Equation of each End of Life Strategy for Permanently Assembled Outsourced Sub Assembly

End of Life Strategy	Recovered Sub Module Quantity	Equation No.
Reuse as Sub Assembly	$\boldsymbol{QPORS\ = 0}$	-
Reuse as Sub Assembly with Recondition	$\boldsymbol{QPOCS\ = 0}$	-
Reuse as Sub Assembly with Repair	$\boldsymbol{QPOPS\ = 0}$	-
Reuse as Sub Assembly with Replacement	$\boldsymbol{QPOLS\ = 0}$	-
Recovered Material	$\boldsymbol{QPOMS\ =\ \sum_{product\ variant}(A\% \times PV \times\ \sum_{module}(QM \times QSM))}$	Equation 4.18

Table 4.6. Equation each End of Life Strategy for Non-Permanently Assembled In-house Part

End of Life Strategy	Recovered Sub Module Quantity	Equation No.
Reuse as Part	$\boldsymbol{QNIRP\ =\ \sum_{product\ variant}((1-I\%) \times (B\% \times A\% + H\% \times (1-B\%) \times A\%) \times PV \times\ \sum_{module}(QM \times QSM))}$	Equation 4.19
Reuse as Part with Recondition	$\boldsymbol{QNICP\ =\ \sum_{product\ variant}(L\% \times I\% \times (B\% \times A\% + H\% \times (1-B\%) \times A\%) \times PV \times\ \sum_{module}(QM \times QSM))}$	Equation 4.20
Reuse as Part with Repair	$\boldsymbol{QNIPP\ =\ \sum_{product\ variant}(J\% \times (1-H\%) \times (1-B\%) \times A\% \times PV \times\ \sum_{module}(QM \times QSM))}$	Equation 4.21
Recovered Material	$\boldsymbol{QNIMP\ =\ \sum_{product\ variant}(((1-J\%) \times (1-H\%) \times (1-B\%) \times A\% + (1-L\%) \times I\% \times (B\% \times A\% + H\% \times (1-B\%) \times A\%)) \times PV \times\ \sum_{module}(QM \times QSM))}$	Equation 4.22

Table 4.7. Equation each End of Life Strategy for Permanently Assembled In-house Part

End of Life Strategy	Recovered Sub Module Quantity	Equation No.
Reuse as Part	$\boldsymbol{QPIRP = 0}$	-
Reuse as Part with Recondition	$\boldsymbol{QPICP = 0}$	-
Reuse as Part with Repair	$\boldsymbol{QPIPP\ =\ \sum_{product\ variant}(K\% \times A\% \times PV \times\ \sum_{module}(QM \times QSM))}$	Equation 4.23

Recovered Material	$QPIMP = \sum_{product\ variant}((1 - K\%) \times A\% \times PV \times \sum_{module}(QM \times QSM))$	Equation 4.24

Table 4.8. Equation each End of Life Strategy for Non-Permanently Assembled Outsourced Part

End of Life Strategy	Recovered Sub Module Quantity	Equation No.
Reuse as Part	$QNORP = \sum_{product\ variant}((1 - I\%) \times (B\% \times A\% + H\% \times (1 - B\%) \times A\%) \times PV \times \sum_{module}(QM \times QSM))$	Equation 4.25
Reuse as Part with Recondition	$QNOCP = \sum_{product\ variant}(L\% \times I\% \times (B\% \times A\% + H\% \times (1 - B\%) \times A\%) \times PV \times \sum_{module}(QM \times QSM))$	Equation 4.26
Reuse as Part with Repair	$QNOPP = 0$	-
Recovered Material	$QNOMP = \sum_{product\ variant}(((1 - H\%) \times (1 - B\%) \times A\% + (1 - L\%) \times I\% \times (B\% \times A\% + H\% \times (1 - B\%) \times A\%)) \times PV \times \sum_{module}(QM \times QSM))$	Equation 4.27

Table 4.9. Equation each End of Life Strategy for Permanently Assembled Outsourced Part

End of Life Strategy	Recovered Sub Module Quantity	Equation No.
Reuse as Part	$QPORP = 0$	-
Reuse as Part with Recondition	$QPOCP = 0$	-
Reuse as Part with Repair	$QPOPP = 0$	-
Recovered Material	$QPOMP = \sum_{product\ variant}(A\% \times PV \times \sum_{module}(QM \times QSM))$	Equation 4.28

As explained in Section 3.4.3 and calculated above, some sub modules cannot be recovered and are used as a recovered material. For the sub assembly type of sub module, which consists of more than one component, the quantity of the recovered material must be calculated based on the unrecovered component quantity. Therefore, the quantity of the recovered material for the sub assembly type of sub module based on the unrecovered component quantity is shown in Table 4.10.

The outputs of this step are the end of life strategies of each sub module with its quantity, the quantity of the unrecovered component with its quantity, and the end of life strategies of the recovered material with its quantity. In addition, the recovery complexity coefficient is also generated for each material of the unrecovered component. The recovery complexity coefficient is a coefficient that determines the difficulty of the process to recover the material. The recovery complexity coefficient is defined to adjust the required time of recovery activities for each material.

Table 4.10. Equation of Unrecovered Component Quantity

Sub Module Type	Recovered Component Quantity	Equation No.
Non-Permanently Assembled In-house Sub Assembly	$\boldsymbol{QNIMSC} = \sum_{product\ variant}(((\mathbf{1}-\boldsymbol{E}\%)\times(\mathbf{1}-\boldsymbol{C}\%)\times(\mathbf{1}-\boldsymbol{B}\%)\times\boldsymbol{A}\% + (\mathbf{1}-\boldsymbol{G}\%)\times\boldsymbol{D}\%\times(\boldsymbol{B}\%\times\boldsymbol{A}\%+\boldsymbol{C}\%\times(\mathbf{1}-\boldsymbol{B}\%)\times\boldsymbol{A}\%))\times\boldsymbol{PV}\times\sum_{module}(\boldsymbol{QM}\times\boldsymbol{QSM}))\times\boldsymbol{QC}\div\boldsymbol{TQC}$	Equation 4.29
Permanently Assembled In-house Sub Assembly	$\boldsymbol{QPIMSC} = \sum_{product\ variant}((\mathbf{1}-\boldsymbol{F}\%)\times(\boldsymbol{B}\%\times\boldsymbol{A}\%+(\mathbf{1}-\boldsymbol{B}\%)\times\boldsymbol{A}\%)\times\boldsymbol{PV}\times\sum_{module}(\boldsymbol{QM}\times\boldsymbol{QSM}))\times\boldsymbol{QC}\div\boldsymbol{TQC}$	Equation 4.30
Non-Permanently Assembled Outsourced Sub Assembly	$\boldsymbol{QNOMSC} = \sum_{product\ variant}((\mathbf{1}-\boldsymbol{C}\%)\times(\mathbf{1}-\boldsymbol{B}\%)\times\boldsymbol{A}\% + (\mathbf{1}-\boldsymbol{G}\%)\times\boldsymbol{D}\%\times(\boldsymbol{B}\%\times\boldsymbol{A}\%+\boldsymbol{C}\%\times(\mathbf{1}-\boldsymbol{B}\%)\times\boldsymbol{A}\%))\times\boldsymbol{PV}\times\sum_{module}(\boldsymbol{QM}\times\boldsymbol{QSM}))\times\boldsymbol{QC}$	Equation 4.31
Permanently Assembled Outsourced Sub Assembly	$\boldsymbol{QPOMSC} = \sum_{product\ variant}(\boldsymbol{A}\%\times\boldsymbol{PV}\times\sum_{module}(\boldsymbol{QM}\times\boldsymbol{QSM}))\times\boldsymbol{QC}$	Equation 4.32

4.7 GENERATING MANUFACTURING PROCESS CHAIN

Some of the attributes of an in-house component such as shape, size tolerance, surface roughness, etc. can be achieved by performing a certain manufacturing process on the component. In a certain case, more than one viable manufacturing process might be used to manufacture the component. In addition, most of the components require a sequence of manufacturing process or a manufacturing process chain to achieve the required attributes (Suteja The, Yarlagadda, Karim, & Yan, 2013). Therefore, this aim of this step is to generate the manufacturing process chain for each in-house component based on its attributes and its production volume. The generated manufacturing process chain will influence the activity and the resource consumed by a product family.

As a large number of shapes and additional features of component exist in practice, these attributes need to be categorised. The basic shape, the shape complexity of the component, and the additional feature attributes are categorised as shown in Sections 4.7.1 and 4.7.2. The existing manufacturing processes are also classified, as explained in Section 4.7.3, to make the selection process more organised and efficient. After that, the strategy to select the manufacturing process effectively and efficiently is shown in Section 4.7.4. Then, how the attributes influence the viable manufacturing process and how to generate the viable manufacturing process chain are explained in Section 4.7.5.

Before proceeding to generate the viable manufacturing processes, the production volume of the in-house component must be calculated by using Equation 4.33. Equation 4.34 and Equation 4.35 show how to calculate the quantity of recovered sub assembly and part type sub modules. In order to generate the viable manufacturing processes, the production volume is then categorised into five ranges: 1 – 100, >100 – 1.000, >1.000 – 10.000, >10.000 – 100.000, and >100.000.

$$\boldsymbol{PVIC} = \sum_{\boldsymbol{product\ variant}}(\boldsymbol{PV} \times \sum_{\boldsymbol{Module}}(\boldsymbol{QM} \times \sum_{\boldsymbol{Sub\ Module}}(\boldsymbol{QSM} \times \boldsymbol{QC}))) - \sum_{\boldsymbol{recovered\ sub\ module}}(\boldsymbol{QRSM} \times \boldsymbol{QC}) + \boldsymbol{QNIMSC} + \boldsymbol{QPIMSC} \qquad \text{Equation 4.33}$$

$$\begin{aligned}\boldsymbol{QRSM}_{\boldsymbol{sub\ assembly\ type}} &= \boldsymbol{QNIRS} + \boldsymbol{QNICS} + \boldsymbol{QNIPS} + \boldsymbol{QNILS} + \boldsymbol{QPIRS} + \boldsymbol{QPICS} \\ &+ \boldsymbol{QPIPS} + \boldsymbol{QPILS} + \boldsymbol{QNORS} + \boldsymbol{QNOCS} + \boldsymbol{QNOPS} + \boldsymbol{QNOLS} \\ &+ \boldsymbol{QPORS} + \boldsymbol{QPOCS} + \boldsymbol{QPOPS} + \boldsymbol{QPOLS}\end{aligned} \qquad \text{Equation 4.34}$$

$$\begin{aligned}\boldsymbol{QRSM}_{\boldsymbol{part\ type}} &= \boldsymbol{QNIRP} + \boldsymbol{QNICP} + \boldsymbol{QNIPP} + \boldsymbol{QPIRP} + \boldsymbol{QPICP} + \boldsymbol{QPIPP} \\ &+ \boldsymbol{QNORP} + \boldsymbol{QNOCP} + \boldsymbol{QNOPP} + \boldsymbol{QPORP} + \boldsymbol{QPOCP} \\ &+ \boldsymbol{QPOPP}\end{aligned} \qquad \text{Equation 4.35}$$

4.7.1 Basic Shapes and Shape Complexity of a Component

The generated in-house component could have various shapes (Bralla, 1999; Esawi & Ashby, 1998; Feng, 2005; Gupta, Chen, Feng, & Sriram, 2003). In this research, the shapes are categorised based on their basic shape and shape complexity. The basic shape consists of round, oval, polygon, tapered round, tapered oval, tapered polygon, dished sheet, deep re-entrant dished sheet, flat sheet, sphere, open section bar, wire, and combination of these basic shapes. The example of each basic shape is shown in Figure 4.9.

The shape complexity of a component can be categorised into solid/no cut outs, hollow/cut outs through, hollow/cut outs opened one end, and hollow/cut outs closed all ends shape complexities. Hollow/cut outs through component means that the component has a hole or a cut out from one face to the other face of the component. Hollow/cut outs opened one end means that the component has a hole or a cut out only on one face. Hollow/cut outs closed all ends means that the component has a hole or a cut out inside the component. Each shape complexity can be divided into five types, which are uniform cross section, stepped/contoured, spatial curvature, transverse/protrusion, and combination of these complexity types. Figure 4.10 shows the example of each complexity type for a polygon.

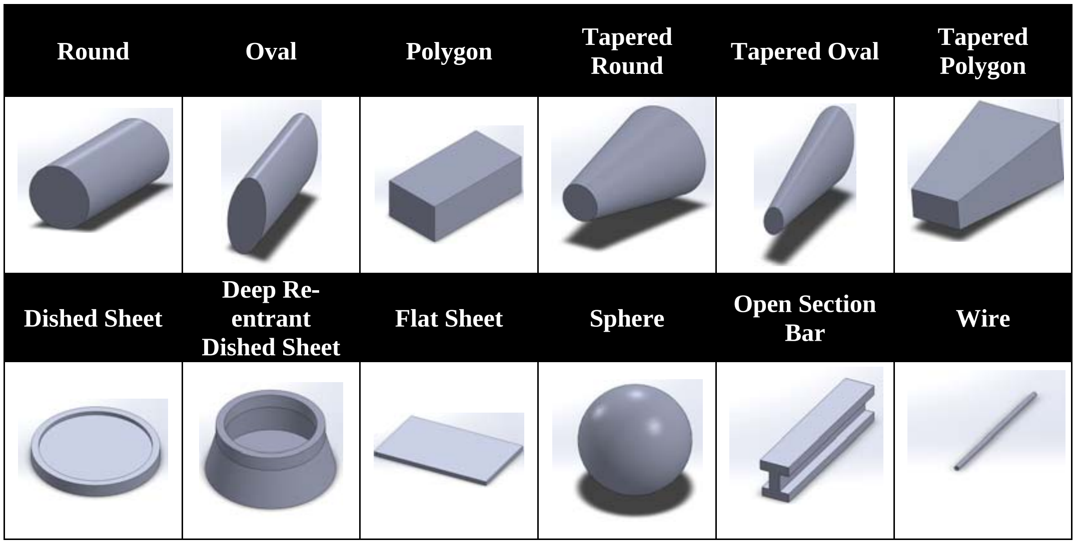

Figure 4.9. Basic Shapes

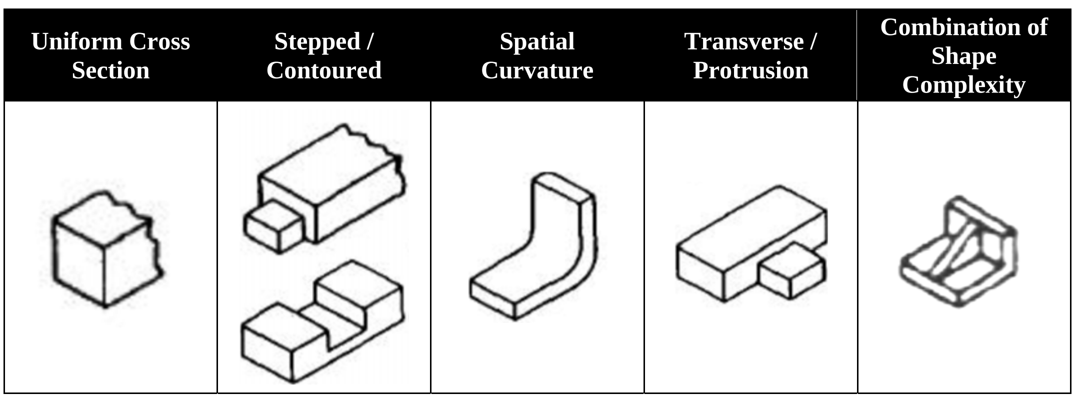

Figure 4.10 Complexity Types of Polygon

4.7.2 Various Additional Features of a Component

Various features of a component exist in the literature (Jung, 2002; Leibl, 1999; Ou-Yang & Lin, 1997; Tseng & Jiang, 2000). Some of the features cannot be manufactured in the same time because of technical or economic constraints. As a result, these features need to be added or subtracted separately. In this research, the additional features are categorised into additive and subtractive features. An additive feature is any geometric form that is added to the main shape of the component. On the other hand, a subtractive feature is any geometric form that is subtracted from the main shape of the component.

The additive features consists of external undercuts, internal undercuts, axial/longitudinal/transversal features, radial features, non-straight features, and spatial curvature. The subtractive features are categorised into external undercuts, internal undercuts, axial/longitudinal/transversal features, radial features, non-straight features, radial holes, and co-axial/longitudinal/transversal holes.

In this research, a subtractive undercut is defined as any concave region such as a local recess that has no regular shape. The subtractive undercut can be categorised into external and internal subtractive undercuts. An external subtractive undercut is a subtractive undercut that is located on the outer side of a component. The example of external subtractive undercut is the recess in the outside diameter of a cylinder. In addition, an internal subtractive undercut is a subtractive undercut that is located on the inner side of a component. An example of an internal subtractive undercut is the recess in the corner of a hollow box.

An additive undercut is any convex region such as a protrusion that has no regular shape. It is also categorised into external and internal additive undercuts. The example of external additive undercut is the protrusion in the outside surface of a box. The example of internal additive undercut is the protrusion inside a hollow cylinder.

The example of an axial/longitudinal/transversal feature of additive feature is a rib: the example of an axial/longitudinal/transversal feature of a subtractive feature is a straight slot; the example of a radial feature of an additive feature is a flange; then, the example of a radial feature of a subtractive feature is round; the example of a non-straight feature is a thread; and, the example of a spatial curvature is a bended feature.

4.7.3 Classification of Manufacturing Processes

A large number of manufacturing processes exist in practice. For that reason, they need to be classified to make the selection process more organised and efficient. In this research, the available manufacturing processes are classified into primary, secondary, and tertiary types according to the classification by Esawi and Ashby (1998). A primary manufacturing process forms a certain shape to a component. A primary manufacturing process transforms unshaped or granular material and gives it shape. A secondary manufacturing process modifies and adds a feature to an already shaped component. Finally, a tertiary manufacturing process adds certain quality to a component without affecting its shape and the feature geometry. Tertiary manufacturing is further categorised into tertiary manufacturing processes to achieve the required size tolerance, surface roughness, material property, and surface finish.

In addition to the three types of manufacturing process, several manufacturing processes are categorised into cutting process. The cutting process type is excluded from the three manufacturing process types to incorporate the need to cut the raw material before the raw material is further processed by using the secondary process.

4.7.4 Manufacturing Process Selection Strategy

There are two approaches in selecting the viable manufacturing process (Lovatt & Shercliff, 1998a, 1998b). In the first approach, the existing manufacturing processes are evaluated in parallel. It means that manufacturing processes are screened and eliminated based on all criteria simultaneously. Then, the viable manufacturing processes, which meet all the design criteria, will be retrieved and suggested. On the other approach, the existing manufacturing processes are evaluated in sequence. The manufacturing processes are screened and eliminated based on each criterion, stage by stage, until viable manufacturing processes are selected. Compared to the parallel approach, this sequential selection approach allows greater detail to be shown at each stage and more refined manufacturing process information can be accessed. It allows more information to be considered before selecting the most viable manufacturing process. However, the use of this approach requires more time during the selection process compared to the parallel approach.

In selecting the manufacturing processes, this proposed system implements a combination of the parallel and sequential selection approaches. In this system, matrix material and production volume developed by Swift and Booker (2003) are used in the first selection sequence to reduce the search range for the next steps. Then, other selection criteria such as shape, envelope size, etc. are used to find the viable manufacturing processes.

4.7.5 Manufacturing Process Chain Generation

Fourteen steps are proposed to generate the manufacturing process chain for each in-house component as shown in Figure 4.11. It starts with the generation of viable primary manufacturing processes for the main shape until the generation of the manufacturing process chain (Bralla, 1999; Esawi & Ashby, 1998; Lovatt & Shercliff, 1998a, 1998b; Suteja The, et al., 2013; Swift & Booker, 2003). A guideline including flowcharts to generate the manufacturing process chain for various complex components is described in Appendix B.

The main shape of the in-house component can be manufactured directly from the granular material by using a primary manufacturing process, or modified from an initially shaped raw material such as bar, tube, etc. by using a secondary manufacturing process. Therefore, the system offers these manufacturing process options in manufacturing the main shape of the in-house component.

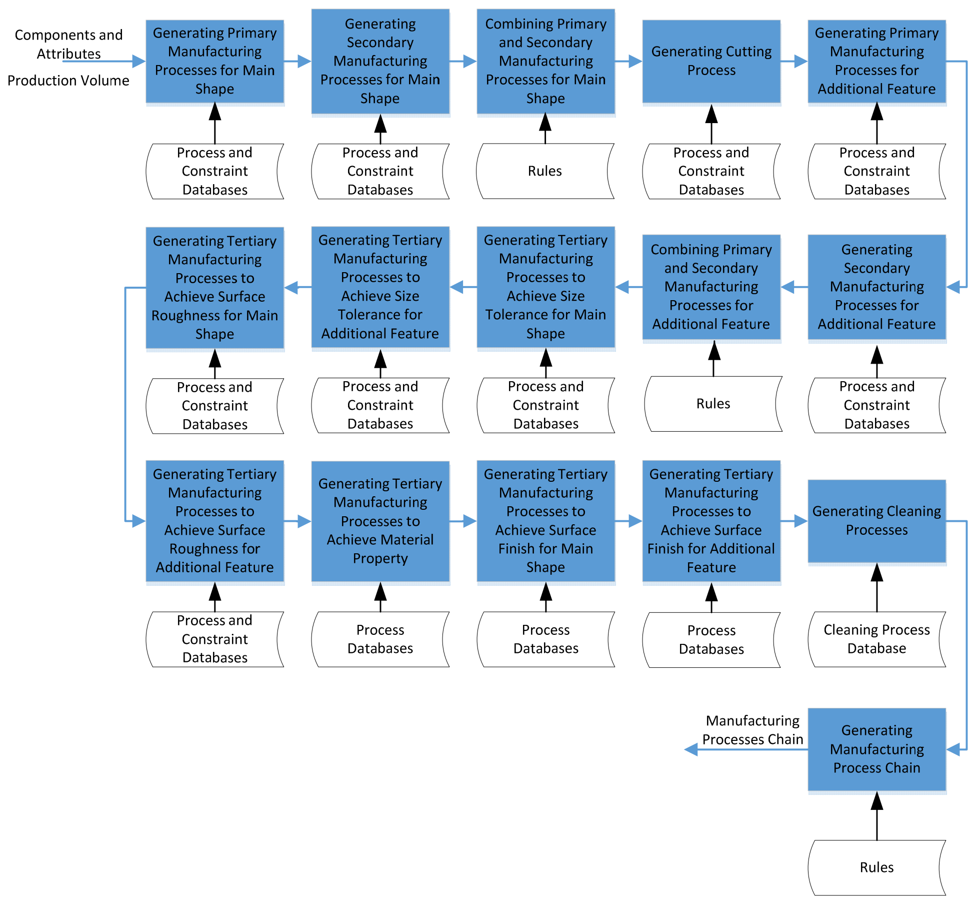

Figure 4.11. Generating Manufacturing Process Chain

The steps required to generate the viable primary manufacturing processes for the main shape of each in-house component are shown in Figure 4.12. First, the material and the production volume of the in-house component are used as the inputs to find all primary manufacturing processes that can be used to manufacture the material in the range of the production volume. Then, the proposed system finds all manufacturing processes that can be used to manufacture the basic shape and the shape complexity type of in-house component by using the basic shape and the shape complexity type as the inputs. Third, the primary manufacturing processes found in the first and second steps are intersected to find the primary manufacturing processes that can manufacture the in-house component with the material, the basic shape, and the shape complexity type in the range of the required production volume. Finally, the intersected primary manufacturing processes are evaluated as to whether they could manufacture the in-house component with the required envelope size and the weight. The outputs of this step are all viable primary manufacturing processes for manufacturing the in-house component and the size tolerance and surface roughness that can be achieved by using each viable primary manufacturing process.

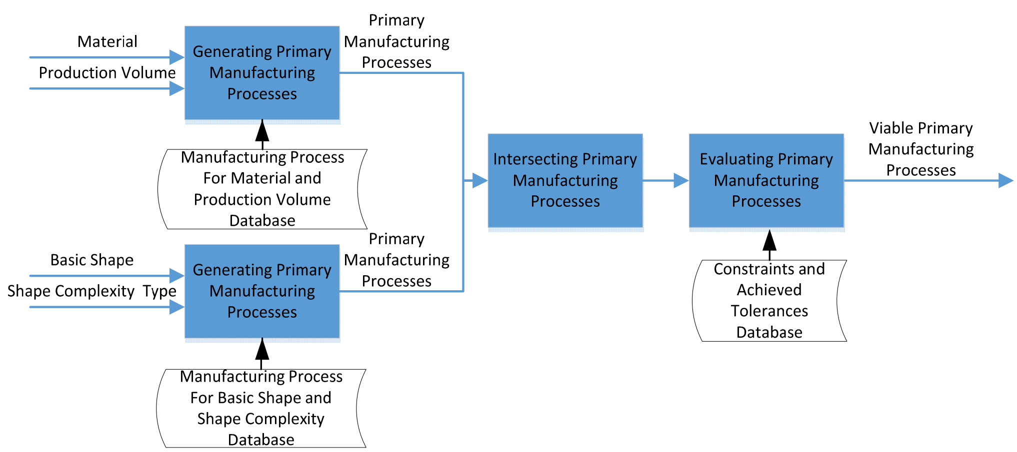

Figure 4.12. Generating Viable Primary Manufacturing Processes for Main Shape

Next, the generation of viable secondary manufacturing processes requires four steps as shown in Figure 4.13. The first stage is the same with the generation of viable primary manufacturing processes. All viable secondary manufacturing processes that can be used to manufacture the material of the in-house component in the range of the production volume are searched. Then, the basic shape and the shape complexity type of in-house component are used to find the viable raw material shapes and the viable secondary manufacturing processes that are able to manufacture each raw material shape into the in-house component. The raw material shape is that already shaped of raw material such as bar, tube, etc. The third and the last steps of the generation of the viable secondary manufacturing processes are similar to the generation of viable primary manufacturing processes. The outputs of this step are all viable raw material shapes, the viable secondary manufacturing processes for manufacturing the in-house component, and the size tolerance and surface roughness that can be achieved by using each viable secondary manufacturing process.

After the viable primary and secondary manufacturing processes for the main shape are generated, they are combined to generate the viable primary and secondary manufacturing processes to manufacture the main shape of the in-house component. The viable primary and secondary manufacturing processes are used to generate the manufacturing process chain.

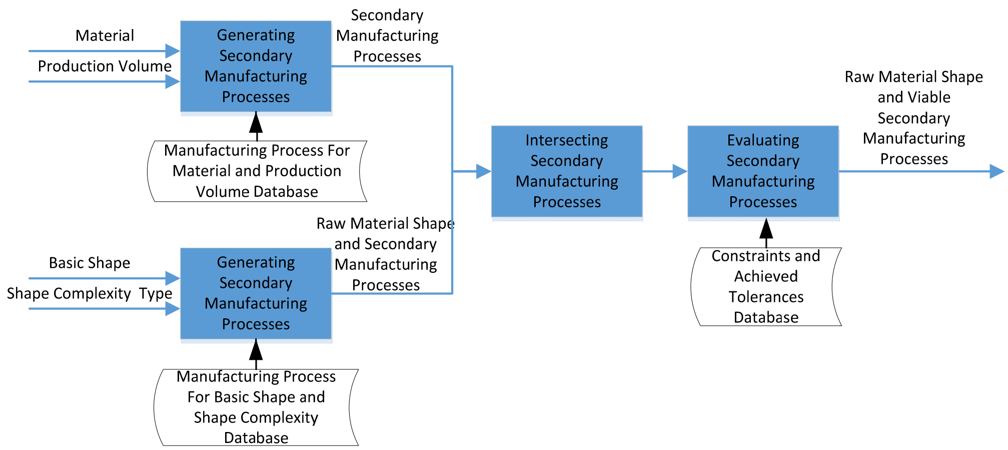

Figure 4.13. Generating Viable Secondary Manufacturing Processes for Main Shape

The viable cutting processes are used to cut the raw material shape. The viable cutting process is generated based on the material, the thickness/height, and the weight of the in-house component as shown in Figure 4.14. The cutting processes are generated as the follow up of the generated viable secondary manufacturing processes. Therefore, the generation of the viable cutting processes will be conducted if the first process in the manufacturing process chain is one of the secondary manufacturing processes. If this is the case, then the viable cutting processes are used to generate the manufacturing process chain.

The generation of viable primary manufacturing process for an additional feature will be conducted if the in-house component has some features that must be added or subtracted separately from the main shape because of technical or economic constraints. The generation processes for the additional feature are similar to those for the main shape. The additional feature of the in-house component can be manufactured directly from the granular material by using a primary manufacturing process or modified from an already shape of raw material such as bar, tube, etc. by using a secondary manufacturing process. Therefore, the system generated these options in manufacturing the additional feature of the in-house component. The steps for generating the viable primary manufacturing processes for the additional feature are shown in Figure 4.15.

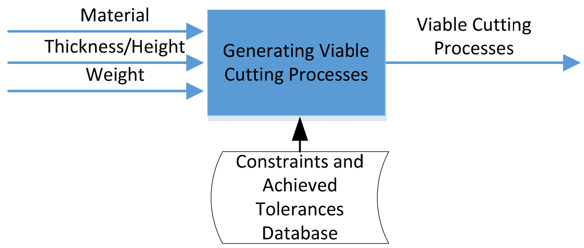

Figure 4.14. Generating Viable Cutting Processes

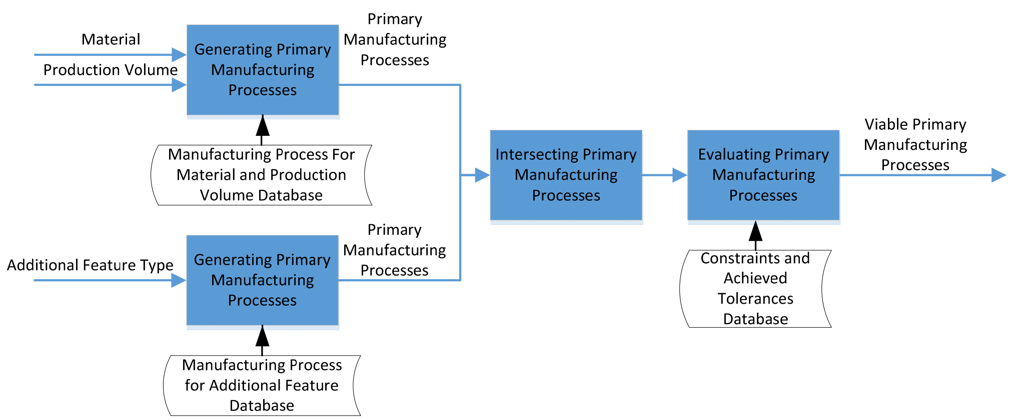

Figure 4.15. Generating Viable Primary Manufacturing Processes for Additional Feature

First, the material and the production volume of the additional feature are used as the inputs to find all viable primary manufacturing processes to manufacture the material of the additional feature in the range of the production volume. The production volume of the additional feature is calculated by multiplying the production volume of the in-house component with the quantity of additional features. Second, the system uses the type of the additional feature to find the viable primary manufacturing processes. Then, the rest of the steps are the same with the generation viable process for the main shape. The outputs of this step are all viable primary manufacturing processes for manufacturing the additional feature and the size tolerance and surface roughness that can be achieved by using each viable primary manufacturing process.

Next, the generation of the viable secondary manufacturing processes for the additional feature will be conducted if the in-house component has at least one additional feature. The steps for generating the viable secondary manufacturing processes for the additional feature are shown in Figure 4.16.

The generation of the viable secondary manufacturing processes for the additional feature are similar to the primary manufacturing processes. First, the material and the production volume of the additional feature are used as the inputs to find all viable secondary manufacturing processes that are able to manufacture the material of the additional feature in the range of the production volume. Second, the system uses the type of the additional feature to find the viable secondary manufacturing processes. Then, the rest of the steps are the same with the generation process for the main shape. The outputs of this step are all viable secondary manufacturing processes for manufacturing the additional feature and the size tolerance and surface roughness that can be achieved by using each secondary manufacturing process.

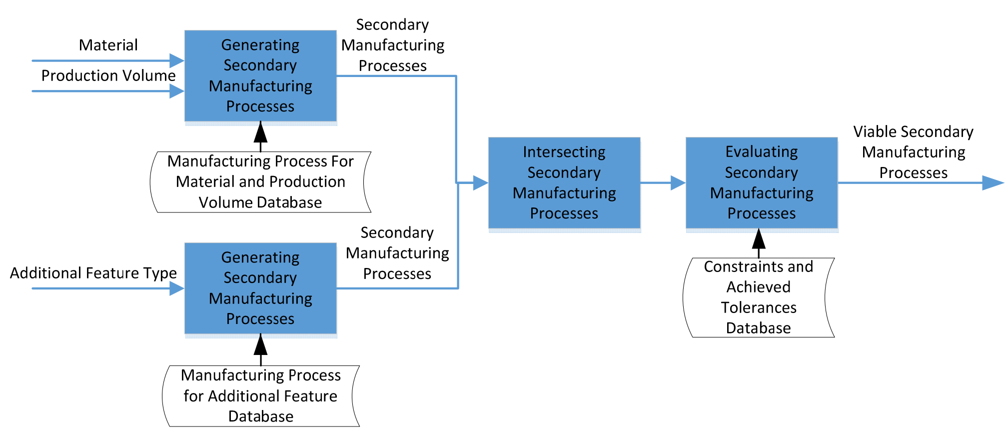

Figure 4.16. Generating Viable Secondary Manufacturing Processes for Additional Feature

Similar to the process for the main shape, the viable primary and secondary manufacturing processes for the additional feature are combined to generate the viable primary and secondary manufacturing processes to manufacture the additional feature. The viable primary and secondary manufacturing processes for the additional feature are used to generate the manufacturing process chain.

The generation of a viable tertiary manufacturing process to achieve the required size tolerance will be conducted if the required size tolerance of the in-house component is not achieved by using the primary or secondary manufacturing processes. The steps for generating the viable tertiary manufacturing process to achieve the required size tolerance are shown in Figure 4.17.

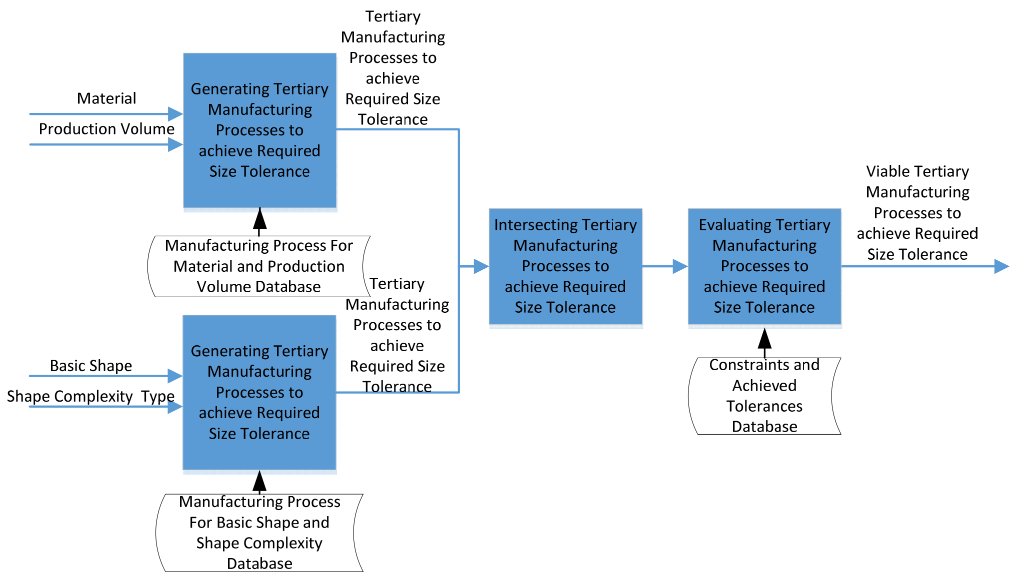

Figure 4.17. Generating Viable Tertiary Manufacturing Process to Achieve the Required Size Tolerance for Main Shape

First, all tertiary manufacturing processes that can be used to manufacture the material in the range of the production volume are searched. Then, all tertiary manufacturing processes that can be used to manufacture the basic shape and the shape complexity type of an in-house component are searched. The tertiary manufacturing processes found in the first and second steps are intersected to find the tertiary manufacturing processes that can manufacture the in-house component with the material, the basic shape, and the shape complexity type in the range of required production volume. Finally, the intersected tertiary manufacturing processes are evaluated, as to whether they could achieve the required size tolerance of the in-house component with the required envelope size. The outputs of this step are all viable tertiary manufacturing processes that can achieve the required size tolerance of the in-house component and the surface roughness that can be achieved by using each tertiary manufacturing process. The viable tertiary manufacturing processes that can achieve the required size tolerance of the in-house component are used to generate the manufacturing process chain.

The generation of a viable tertiary manufacturing process to achieve the required size tolerance for an additional feature will be conducted if the in-house component has at least one additional feature and the required size tolerance of the additional feature is not achieved by using the primary or secondary manufacturing processes. The steps for generating the viable tertiary manufacturing process to achieve the required size tolerance for an additional feature are shown in Figure 4.18.

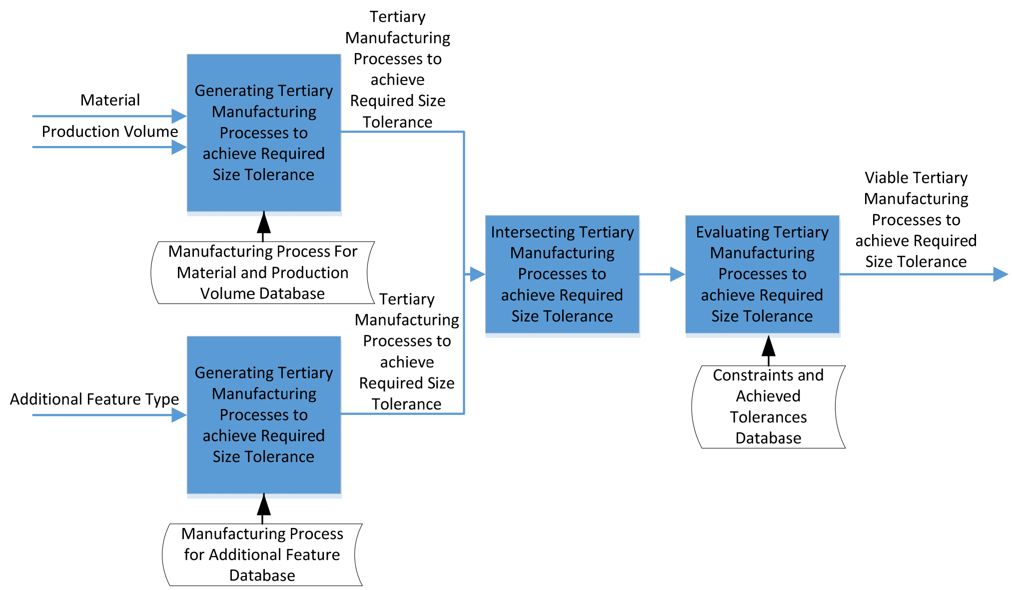

Figure 4.18. Generating Viable Tertiary Manufacturing Processes to Achieve the Required Size Tolerance for Additional Feature

First, all tertiary manufacturing processes that can be used to manufacture the material in the range of the production volume of the additional feature are searched. Then, the system uses the type of the additional feature to find the viable tertiary manufacturing processes. The tertiary manufacturing processes found in the first and second steps are intersected to find the tertiary manufacturing processes that can manufacture the additional feature. Finally, the intersected tertiary manufacturing processes are evaluated, as to whether they could achieve the required size tolerance of the additional feature of in-house component with the required envelope size. The outputs of this step are all viable tertiary manufacturing processes that can achieve the required size tolerance of the additional feature and the surface roughness that can be achieved by using each tertiary manufacturing process. The viable tertiary manufacturing processes that can achieve the required size tolerance of the additional feature are used to generate the manufacturing process chain.

This generation of the viable tertiary manufacturing processes to achieve the required surface roughness is conducted if the required surface roughness of the in-house component is not achieved by using the primary, secondary or previous tertiary manufacturing processes. The steps for generating the viable tertiary manufacturing processes to achieve the required surface roughness are shown in Figure 4.19.

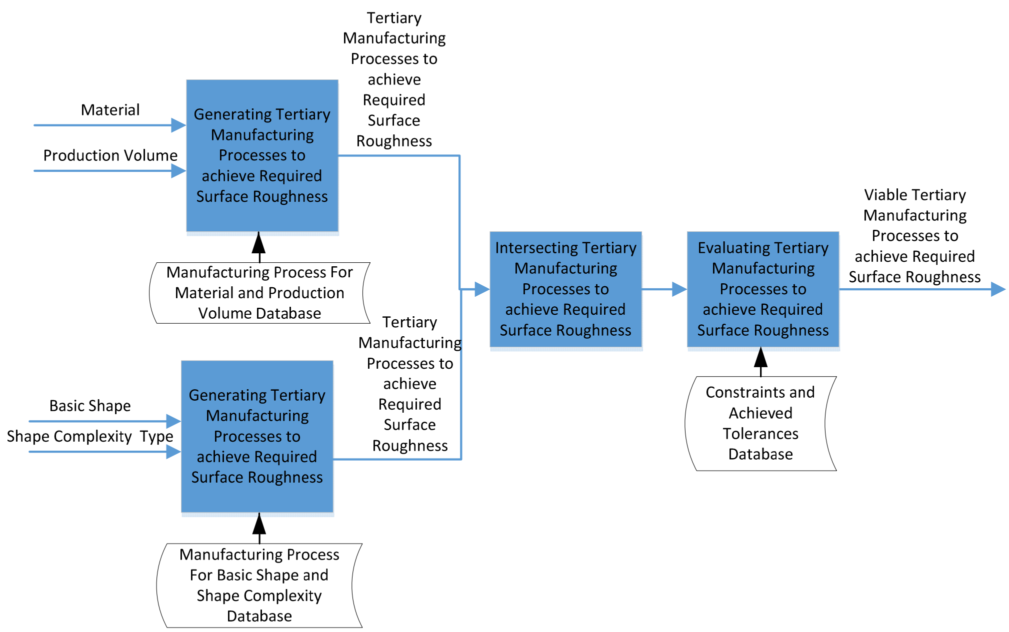

Figure 4.19. Generating Viable Tertiary Manufacturing Processes to Achieve the Required Surface Roughness for Main Shape

The generation of the viable primary manufacturing processes to achieve the required surface roughness are similar to the primary and secondary manufacturing processes. First, the material and the production volume of the in-house component are used as the inputs to find all viable tertiary manufacturing processes to achieve the required surface roughness. Second, the system uses the basic shape and complexity shape type of the in-house component to find all viable tertiary manufacturing processes that can achieve the required surface roughness. Then, the system finds all viable tertiary manufacturing processes that can achieve the required surface roughness for the material, the basic shape, and the complexity shape type of the in-house component in the amount of the required production volume. Finally, the viable tertiary manufacturing processes are evaluated to find those that can achieve the required size tolerance of the in-house component with the required envelope size. The outputs of this step are all viable tertiary manufacturing processes to achieve the required surface roughness of the in-house component. The viable tertiary manufacturing processes that can achieve the required surface roughness of the in-house component are used to generate the manufacturing process chain.

The generation of a viable tertiary manufacturing process to achieve the required surface roughness for an additional feature will be conducted if the in-house component has at least one additional feature and the required surface roughness of the additional feature is not achieved by using the primary, secondary, or previous tertiary manufacturing processes. The steps for generating the viable tertiary manufacturing process to achieve the required surface roughness for an additional feature are shown in Figure 4.20.

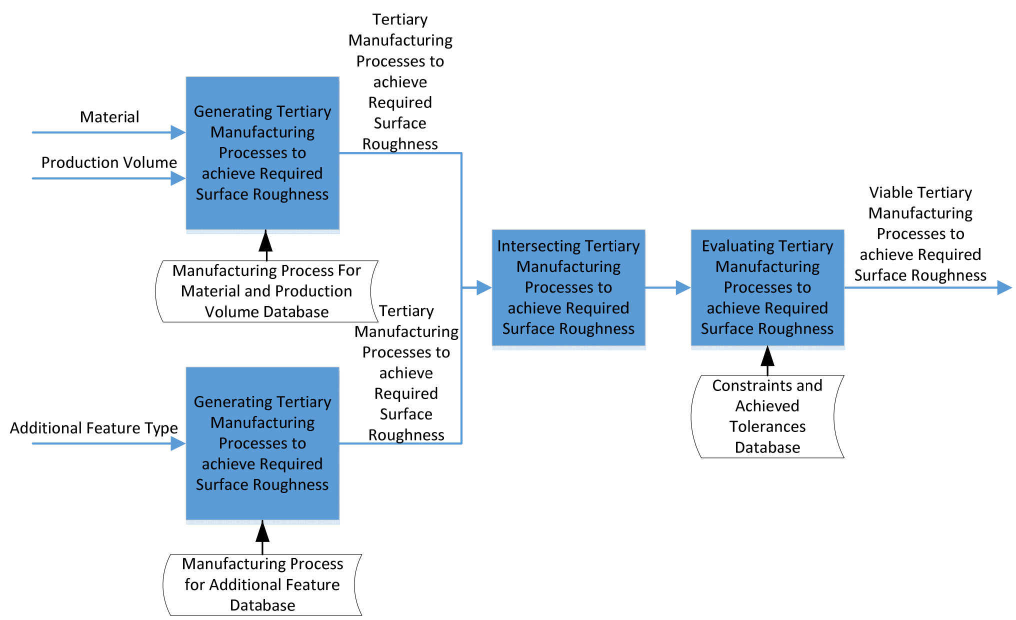

Figure 4.20. Generating Viable Tertiary Manufacturing Processes to Achieve the Required Surface Roughness for Additional Feature

The generation of the viable tertiary manufacturing processes to achieve the required surface roughness for the additional feature are similar to the tertiary manufacturing processes to achieve the required size tolerance. First, all tertiary manufacturing processes to achieve the required surface roughness that can be used to manufacture the material in the range of the production volume of the additional feature are searched. Then, the system uses the type of the additional feature to find the viable tertiary manufacturing processes to achieve the required surface roughness for the additional feature. The tertiary manufacturing processes found in the first and second steps are intersected to find those that can manufacture the additional feature. Finally, the intersected tertiary manufacturing processes are evaluated as to whether they could achieve the required surface roughness of the additional feature of an in-house component with the required envelope size. The outputs of this step are all viable tertiary manufacturing processes to achieve the required surface roughness of the additional feature of an in-house component. The viable tertiary manufacturing processes that can achieve the required surface roughness of the additional feature of the in-house component are used to generate the manufacturing process chain.

The generation of the viable tertiary manufacturing processes to achieve the required material property will be conducted if the in-house component requires that a certain property of its material be modified. The viable tertiary manufacturing processes to achieve the required material property is generated based on the material and the required material property of the in-house component as shown in Figure 4.21. The outputs of this step are all viable tertiary manufacturing processes to achieve the required material property of an in-house component. The viable tertiary manufacturing processes to achieve the required material property are used to generate the manufacturing process chain.

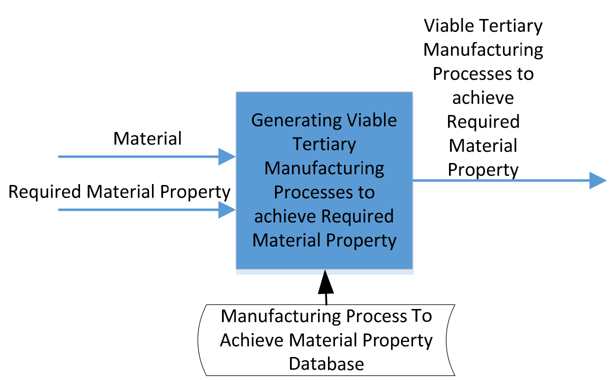

Figure 4.21. Generating Viable Tertiary Manufacturing Processes to Achieve the Required Material Property

Three steps are used to generate the viable tertiary manufacturing processes to achieve the required surface finish of each in-house component as shown in Figure 4.22. The generation process will be conducted if the in-house component requires achieving certain surface finish.

First, the proposed system finds all tertiary manufacturing processes that can be used to achieve the required surface finish for the material of the in-house component. Then, all tertiary manufacturing processes that can be used to manufacture the basic shape and the shape complexity type of the in-house component are searched. Finally, the manufacturing processes found in the first and second steps are intersected to find the tertiary manufacturing processes that can provide the in-house component with the required surface finish. The outputs of this step are all viable tertiary manufacturing processes to achieve the required surface finish of each in-house component. The viable tertiary manufacturing processes to achieve the required surface finish of the in-house component are used to generate the manufacturing process chain.

This generation of the viable tertiary manufacturing processes to achieve the required surface finish for an additional feature will be conducted if the in-house component has at least one additional feature and the additional feature requires achieving certain of surface finish. Figure 4.23 shows the steps to generate the viable tertiary manufacturing processes to achieve the required surface finish for an additional feature.

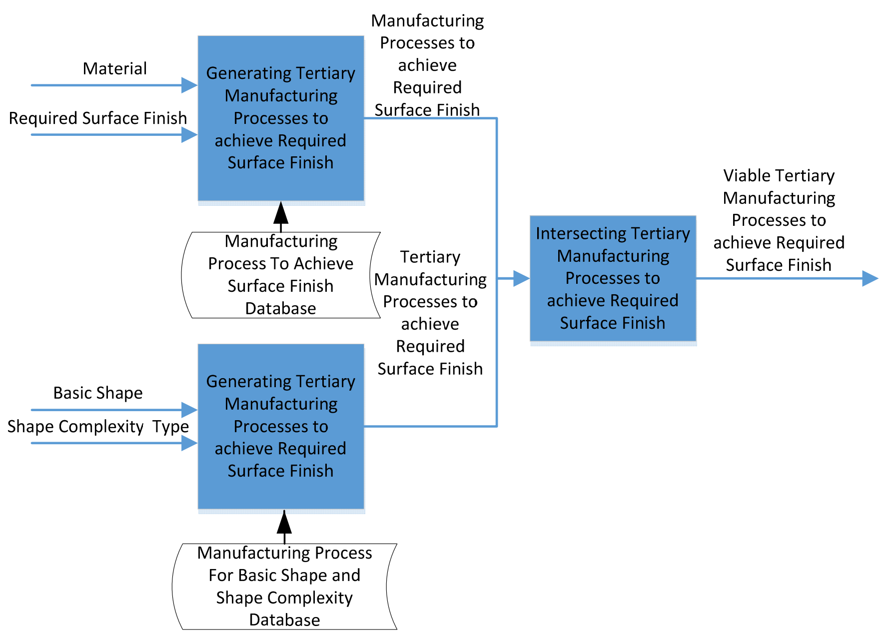

Figure 4.22. Generating Viable Tertiary Manufacturing Processes to Achieve the Required Surface Finish for Main Shape

First, all tertiary manufacturing processes that can be used to achieve the required surface finish for the in-house component material are searched. Then, the system finds all tertiary manufacturing processes that can be used to manufacture the additional feature of an in-house component. Finally, the manufacturing processes found in the first and second steps are intersected to find the tertiary manufacturing processes that can provide the additional feature of the in-house component with the required surface finish. The outputs of this step are all viable tertiary manufacturing processes to achieve the required surface finish of the additional feature of each in-house component. The viable tertiary manufacturing processes to achieve the required surface finish of the additional feature are used to generate the manufacturing process chain.

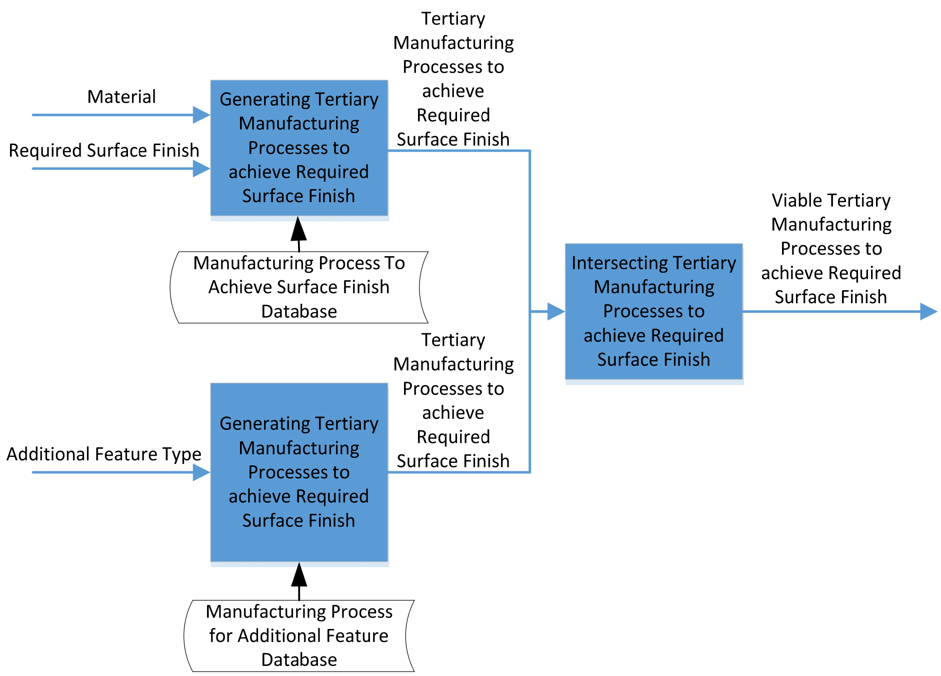

Figure 4.23. Generating Viable Tertiary Manufacturing Processes to Achieve the Required Surface Finish for Additional Feature

In addition to the manufacturing process and cutting process, one or more cleaning processes are required before conducting the tertiary manufacturing process to achieve the required surface finish. The viable cleaning processes are determined based on the type of tertiary manufacturing process to achieve the required surface finish and the process type prior to the tertiary manufacturing process to achieve the required surface finish, as shown in Figure 4.24. If the in-house component has one or more additional features and the additional feature requires a tertiary manufacturing process to achieve the surface finish, then the viable cleaning processes are not only generated for the in-house component but also for the additional feature. The viable cleaning processes are used as an additional process for the manufacturing process chain.

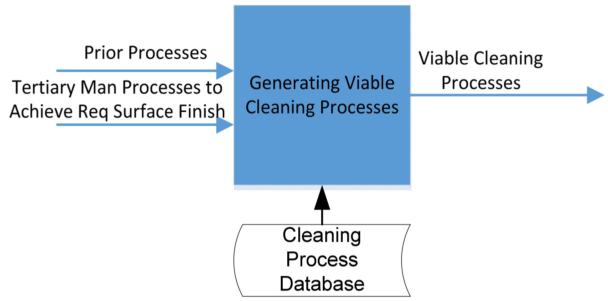

Figure 4.24. Generating Viable Cleaning Processes

In order to generate the manufacturing process chain, one of the viable primary and secondary manufacturing combination processes is selected as the first process of the manufacturing process chain. If the first process of the manufacturing process chain is the secondary manufacturing process type, the viable cutting processes will be generated. Then, one of the viable cutting processes must be selected as the second process of the manufacturing process chain.

If the in-house component has at least one additional feature, the next process of the manufacturing process chain will be selected from the viable primary and secondary manufacturing combination processes for the additional feature. If the selected manufacturing process for the main shape is the primary manufacturing process type then only the same primary manufacturing process or one of the viable secondary manufacturing processes can be selected as the process for the additional feature. If the selected manufacturing process for the additional feature is the same process with the selected manufacturing process for the main shape, the additional feature must be able to be manufactured together with the main shape. It means that no manufacturing process for the additional feature is added to the manufacturing process chain. If the selected manufacturing process for the main shape is the secondary manufacturing process type, then the viable primary manufacturing process for the additional feature cannot be selected.

Then, if the required size tolerance is not yet achieved by using the previous manufacturing processes, one of the viable tertiary manufacturing processes that can achieve the required size tolerance of the in-house component is selected as the next process of the manufacturing process chain. If the in-house component has at least one additional feature and the required size tolerance of the additional feature is not achieved by using the primary or secondary manufacturing processes, the selected process will be added by one of the viable tertiary manufacturing processes that can achieve the required size tolerance of the additional feature.

The next process of the manufacturing process chain is selected from the viable tertiary manufacturing processes to achieve the required surface roughness. This selection is conducted if the required surface roughness is not yet achieved by using the previous manufacturing processes. If the in-house component has at least one additional feature and the required surface roughness of the additional feature is not achieved by using the previous manufacturing processes, the manufacturing process chain will be added by one of the tertiary manufacturing processes to achieve the required surface roughness for additional feature.

If the in-house component requires modifying a certain property of its material, then the next process will be selected from the viable tertiary manufacturing processes to achieve the required material property of the in-house component.

Next, if the in-house component requires achieving a certain surface finish, one of the viable tertiary manufacturing processes to achieve the required surface finish for main shape will be selected as the next process of the manufacturing process chain. If the in-house component has at least one additional feature and the additional feature requires achieving a certain surface finish, then one of the viable tertiary manufacturing processes to achieve the required surface finish for the additional feature will be selected as the next process of the manufacturing process chain. If a basic surface finishing process is required as an additional surface finish, then the basic surface finishing process will be listed before the viable tertiary manufacturing processes to achieve the required surface finish for the main shape. The basic surface finishing process is the surface finishing process that is required to be conducted before another surface finishing process is conducted.

Finally, one or more cleaning processes are selected as the additional process for the manufacturing process chain. The selected cleaning process is listed before the tertiary manufacturing process to achieve the required surface finish. If the in-house component requires more than one tertiary manufacturing process to achieve the required surface finish then it will also require more than one cleaning process. If the in-house component has one or more additional features and the additional feature requires a tertiary manufacturing process to achieve the surface finish, then the viable cleaning process is not only selected for the in-house component but also for the additional feature.

4.8 GENERATING OUTSOURCING PROCESS

The outsourcing process is how the outsourced material and outsourced component are procured to fulfil the production requirement. The steps to generate an outsourcing process for material and outsourced component is presented in Figure 4.25. To procure the outsourced material, the inputs are the required raw material and the shape of the raw material of the in-house component. The system will generate the viable supplier names, their region, their minimum order, their batch order, and the price of the material. Then, one of the viable supplier names is selected as the supplier. Finally, the system calculates the volume of each in-house component, the volume of material to manufacture the required in-house components, the weight of the material that must be purchased, and the quantity of purchase orders for each in-house component in order to calculate the life cycle cost in Section 4.10. The generated outsourcing process will influence the rate of the outsourced material and outsourced component. In addition, it will also influence the activity cost calculated in Section 4.10.

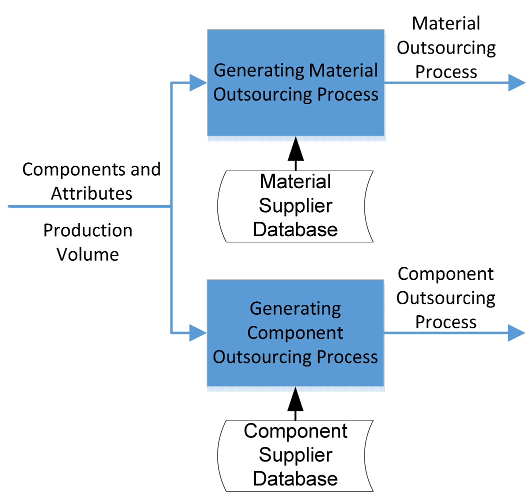

Figure 4.25. Generating Outsourcing Process

The quantity of purchased material orders is calculated by dividing the total purchased weight of material with the batch order. If the quantity of purchased orders is not an integer, then it will be rounded up as shown in Equation 4.36. To calculate the quantity of purchased material orders for each in-house component, the result is divided by the number of in-house components that use the material. The total purchase weight of each material can be calculated as shown in Equation 4.37 below. Equation 4.38 and Equation 4.39 show how to calculate the quantity of the required material weight of component and the total recovered material weight. The total quantity of unrecovered components is shown in Equation 4.40.

$$\boldsymbol{QPMO = ROUNDUP\left(\frac{TPWM}{MBO}\right)}$$ Equation 4.36

$$\boldsymbol{TPWM = \sum\nolimits_{In-house\ Part\ Type\ Component\ with\ the\ Same\ Material}(RMWC) - TRMW}$$ Equation 4.37

$$\boldsymbol{RMWC = \sum\nolimits_{Product\ Variant}(PV \times \sum\nolimits_{Module}(QM \times \sum\nolimits_{Sub\ Module}(QSM \times QC \times WC))) - \sum\nolimits_{Recovered\ Sub\ Module}(QRSM \times QC \times WC)}$$ Equation 4.38

$$\boldsymbol{TRMW = \sum\nolimits_{Recovered\ Component\ with\ the\ Same\ Material}(QCRM \times WC)}$$ Equation 4.39

$$\mathbf{QCRM = QNIMSC + QPIMSC + QNOMSC + QPOMSC + QNIMP + QPIMP + QNOMP + QPOMP}$$ Equation 4.40

The outsourcing process of the outsourced component is slightly different compared to the outsourced material. In outsourcing the outsourced sub module, the information related to the require sub module and its components is used as an input. After that, various viable supplier names, the region of each supplier, the minimum order, the batch order, and the price of the sub module are generated by the system. Then, one of the viable supplier names is selected as the supplier of the sub module. Finally, the purchased quantity of an outsourced component and the quantity of outsourced component order are calculated by the system.

The quantity of the outsourced component order is calculated by dividing the purchased quantity of an outsourced component with the outsourced component batch order. If the result is not an integer, it will be rounded up as shown in Equation 4.41. The purchased quantity of the outsourced component is calculated by Equation 4.42 below.

$$\boldsymbol{QOCO = ROUNDUP\left(\frac{TPQOC}{OCBO}\right)}$$ Equation 4.41

$$\mathbf{TPQOC = \sum\nolimits_{Product\ Variant}(PV \times \sum\nolimits_{Module}(QM \times \sum\nolimits_{Sub\ Module}(QSM \times QC))) - \sum\nolimits_{Recovered\ Sub\ Module}(QRSM \times QC)}$$ Equation 4.42

4.9 GENERATING ACTIVITY AND RESOURCE

In this step, the generated information from the previous steps is used as inputs to generate the information related to activity and resource. This step allocates the activities and resources into each component level of a product family as a basis to allocate the cost. The knowledge-based system explained in Section 3.6 is used to generate the activity and resource information. First, all required activities and resources consumed by each component are generated. The generation of the activities and resources consumed by the component are described in Section 4.9.1. Then, all activities and resources consumed by each product platform and product variant are generated. Section 4.9.2 describes the activity and resource generation process for product platform and product variant. After that, how to generate the activity and resource required by a taken back product is explained in Section 4.9.3. Finally, Section 4.9.4 described the process to generate the activity and resource of the recovered sub module and recovered material.

After the activity and resource information are generated, the system generates information related to the activity driver and its quantity, the required time, the cost categorisation, and the life cycle stage of each activity in order to estimate the life cycle cost of each component level of a product family. The activity driver is a factor that influences the consumption of the activity. The quantity of the activity driver is the required amount or number of the activity driver consumed by a part or a product. The system also generates the required time to perform each activity for each component, product platform, product variant, taken back product, recovered material, and recovered sub module. The cost categorisation and the life cycle stage for each activity refer to the categorisation outlined in Table 2.1.

As some activities are more complicated and difficult than others, three coefficients have been defined to adjust the required time in performing the activities. The coefficients that have been described in Section 4.3, Section 4.5, and Section 4.6 are used as a multiplier of the required time. First, a manufacturing complexity coefficient is used to adjust the required time of manufacturing process activities for each in-house component. Second, an assembly/disassembly complexity coefficient is used to adjust the required time of assembly process and disassembly process activities for each assembly sequence of a component. Last, a recovery complexity coefficient is used to adjust the required time of recovery activities for each material.

4.9.1 Generating Activity and Resource for Component

This step generates the activity and resource information for both in-house and outsourced components. First, the procurement strategy generated in Section 4.3 is used as the input to generate the general activities of each component and the department where each activity is conducted. The general activity is the activity that is not related to any process manufacturing or assembly. If the procurement strategy is outsourced, the required activities for the outsourced component and the departments where each activity is conducted will be generated. The steps to generate the activities for an outsourced component are shown in Figure 4.26. The resources consumed by the activity are all resources that are available in the embedded departments. Therefore, the resources consumed by the outsourced component are all the resources in the generated departments.

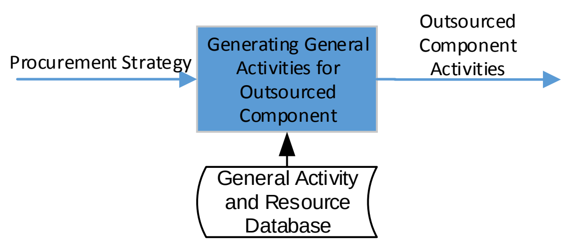

Figure 4.26. Generating Activities for Outsourced Component

Figure 4.27 presents the steps to generate the activities for an in-house component. The generated activities include all required activities for its additional features. The in-house component activities consist of general and manufacturing process activities. For each in-house component, the procurement strategy generated in Section 4.3 is used as the input to generate the required general process activities and the general process department where each activity is conducted. After that, the manufacturing process chain generated in Section 4.7 is used as the input to generate the manufacturing process activities and the manufacturing process departments for the main shape and the additional feature of the in-house component. Similar to the outsourced component, the resources consumed by the in-house component are all the resources in the generated general process and manufacturing process departments.

4.9.2 Generating Activity and Resource for Product Platform and Product Variant

Figure 4.28 shows how to generate the required activities for a product platform and a product variant. The product platform and product variant require general process and assembly process activities and their departments. The general process activities with their departments required by a product platform are different compared to a product variant. Therefore, the general activities with the departments for a product platform and product variant are generated based on their component level. For the product platform level, the system generates the general process activities with their departments for product platform. For the product variant level, the general process activities with their departments for product variant are generated.

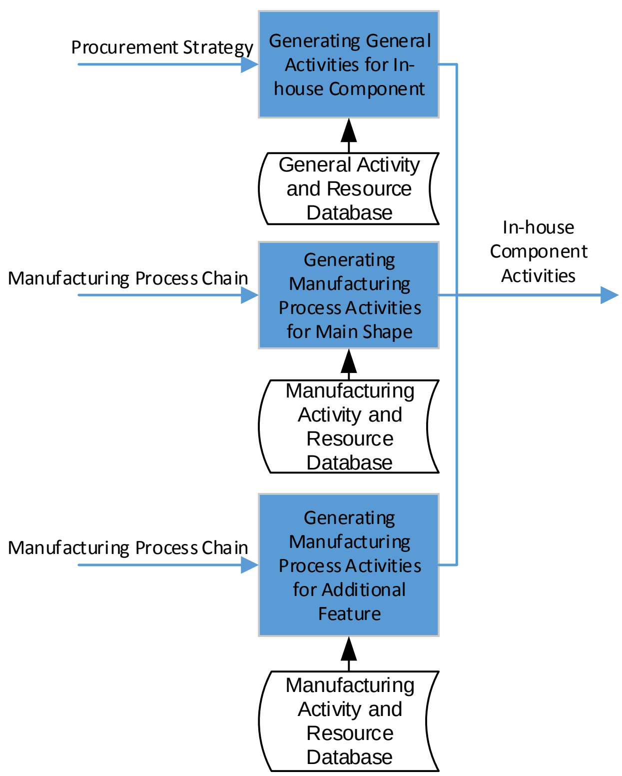

Figure 4.27. Generating Activities for In-house Component

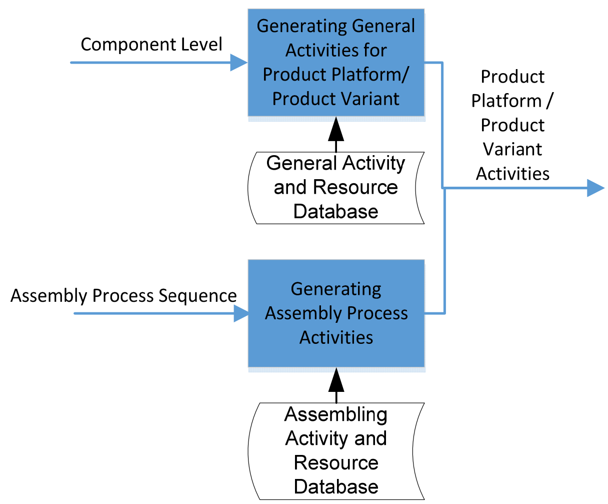

Figure 4.28. Generating Activities for Product Platform and Product Variant

The assembly process activities with their departments are generated based on the assembly process sequence generated in Section 4.5. The generation process is the same for both product platform and product variant. The joining process of the assembly sequence is used as the input to generate the assembly process activities with their departments. For the product platform, the selected joining processes to assemble the product platform are used to generate the assembly process activities with their departments. The product variant assembly process activities with their departments are generated according to the selected joining processes to assemble the variant of the product variant.

Lastly, the resources in the generated general process department and assembly process departments are used as the resources consumed by the product platform and product variant.

4.9.3 Generating Activity and Resource for Taken Back Product

The steps to generate the activities consumed by a taken back product are shown in Figure 4.29. The activities and resources required by a taken back product consist of general process and disassembly process activities. First, the general process activities with their departments are generated. Then, the disassembly process activities with their departments are generated according to the degree of permanence of each assembly sequence. Finally, the resources consumed by the taken back product are generated based on the resources in the generated general process and disassembly process departments.

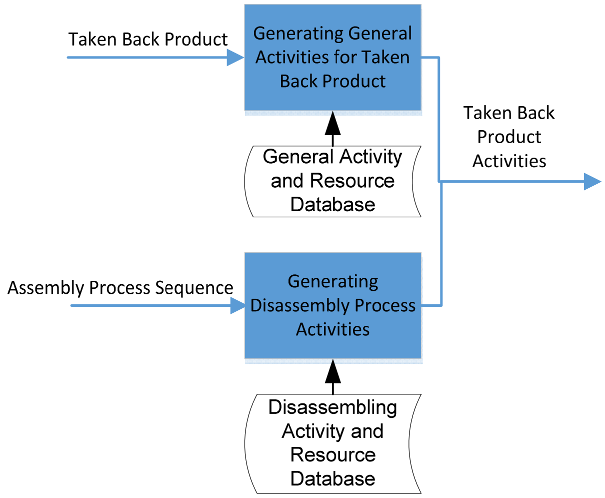

Figure 4.29. Generating Activities for Taken Back Product

4.9.4 Generating Activity and Resource for Recovered Sub Module and Recovered Material

First, the end of life strategy generated in Section 4.6 is used as the input to generate the activities with their departments as required by the recovered sub module and recovered material as shown in Figure 4.30. Then, the resources in the generated departments are used as the resources consumed by the recovered sub module and recovered material.

4.10 CALCULATING LIFE CYCLE COST

In this step, the life cycle cost model that is developed based on the adapted time-driven activity-based costing technique explained in Section 3.3 is used to calculate the rate of the recovered material, the recovered sub module, the in-house component, the product platform, and the product variant. Then, the system calculates the life cycle cost of the in-house component, the product platform, and the product variant based on the method explained in Section 3.4. Figure 4.5 shows the framework in calculating the life cycle cost of each component level of a product family. The first input required to calculate the life cycle cost is the activity and resource information that is already generated in Section 4.9. In addition, various operational parameters, quality parameters, inventory parameters, market parameters, financial parameters, and end of life parameters are also retrieved from the parameter databases as the inputs. These parameters are calculated based on one year range estimation.

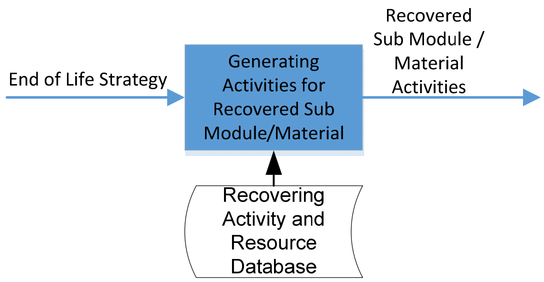

Figure 4.30. Generating Activities for Recovered Sub Module and Recovered Material

4.10.1 Calculating Recovered Material Rate

The steps to calculate the rate of a recovered material ($/kg) are shown in Figure 4.31. The recovered material is always a bulk material. Therefore, the recovered material cost is only for bulk material. First, total time usage of each activity for each unrecovered component is calculated by multiplying the activity driver quantity and the required times to perform the activity for each unrecovered component as shown in Equation 4.43. The activity driver quantity and the required times are calculated or taken from the inputted parameters. Then, Equation 4.44 shows how the resource cost of each activity for each unrecovered component is calculated by multiplying the total time usage of each activity for each unrecovered component with the total resource rate of the department required for the activity. The activity cost for each unrecovered component is the summation of the resource cost of all activities for each unrecovered component as shown in Equation 4.45. The rate of the unrecovered component is the summation of the activity cost and the taken back cost of the unrecovered component.

$$\boldsymbol{TTU} = \boldsymbol{QAD} \times \boldsymbol{RTA} \qquad \text{Equation 4.43}$$

$$\boldsymbol{RCA} = \sum_{\boldsymbol{Resources\ of\ Department}} (\boldsymbol{RR}) \times \boldsymbol{TTU} \qquad \text{Equation 4.44}$$

$$\boldsymbol{TAC} = \sum_{\boldsymbol{Activities}} (\boldsymbol{RCA}) \qquad \text{Equation 4.45}$$

For the unrecovered component that has recyclable material, the recovered material rate is calculated. First, the activity cost for all unrecovered components that have the same recyclable material and the taken back cost of the unrecovered components are summed as the total cost of the recovered material as shown in Equation 4.46. The taken back cost of the components is calculated by multiplying the estimated percentage of the remaining value of the component at its end of life with the new component rate. The rate of the recovered material is calculated by dividing the total cost of the recovered material with the total weight of the recovered material as shown in Equation 4.47. The total weight of the recovered material is calculated by summing the weight of all components that are made of the material. The total cost and the total weight of the recovered material are calculated for each product family.

$$TCRM = \sum_{Recovered\ Component\ with\ the\ Same\ Material} (TAC + TBC) \qquad \text{Equation 4.46}$$

$$RRM = \frac{TCRM}{TRMW} \qquad \text{Equation 4.47}$$

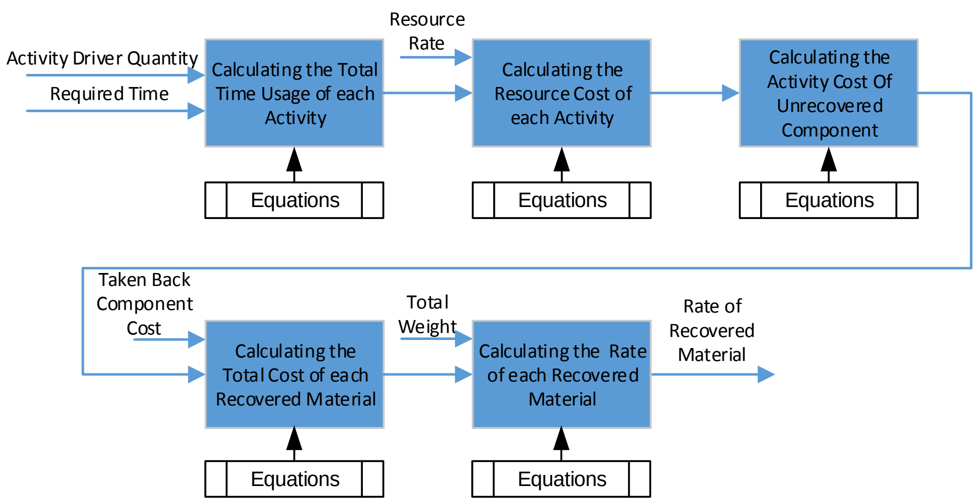

Figure 4.31. Calculating the Rate of Recovered Material

4.10.2 Calculating Recovered Sub Module Rate

Next, Figure 4.32 shows how to calculate the rate of a recovered sub module ($/unit). Similar to the recovered material, the total activity cost for each recovered sub module is first calculated. Then, the rate of the recovered sub module is calculated. First, the total time usage of each activity for each recovered sub module is calculated by multiplying the activity driver quantity and the required times to perform the activity as shown in Equation 4.43. Then, Equation 4.44 shows how the resource cost of each activity is calculated by multiplying the resource rate for each department with the total time usage of each activity. The total activity cost for each recovered sub module is the summation of the resource cost of all activities consumed by each recovered sub module as shown in Equation 4.45.

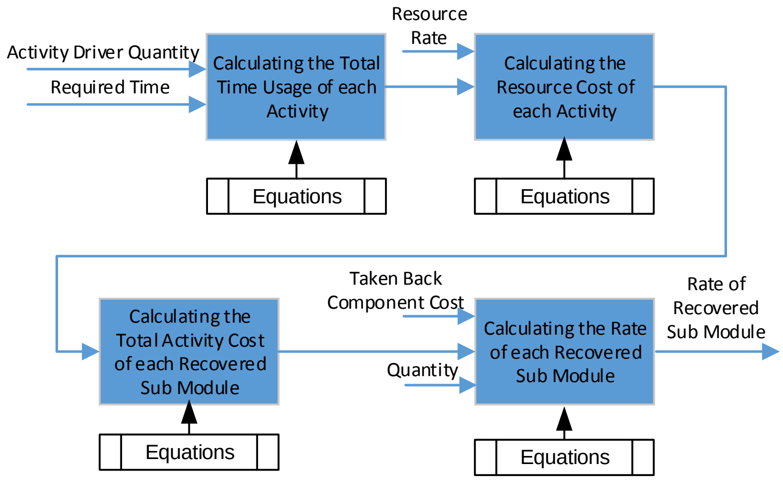

Figure 4.32. Calculating the Rate of Recovered Sub Module

The rate of the recovered sub module is calculated by dividing the summation of the total activity cost and the total taken back cost of the component of the recovered sub module by the quantity of the recovered sub module as shown in Equation 4.48. The quantity of the recovered sub module is calculated by summing the quantity of the recovered sub modules for all end of life strategies as shown in Equation 4.34 and. The total cost and the quantity of the recovered sub module are calculated for each product family.

$$\boldsymbol{RRS} = \frac{\boldsymbol{TAC} + \sum_{\boldsymbol{component\ of\ sub\ module}} \boldsymbol{TBC}}{\boldsymbol{QRSM}} \qquad \text{Equation 4.48}$$

4.10.3 Calculating Component Rate

The steps to calculate the rate of an in-house component ($/unit) are shown in Figure 4.33. First, the cost of recovered material used by the in-house component is calculated. Second, the cost of raw material used by the in-house component is calculated. After that, the system calculates the storage cost of the in-house component and its material. Then, the cost of all activities consumed by the in-house component is calculated. Finally, the system calculates the rate of the in-house component.

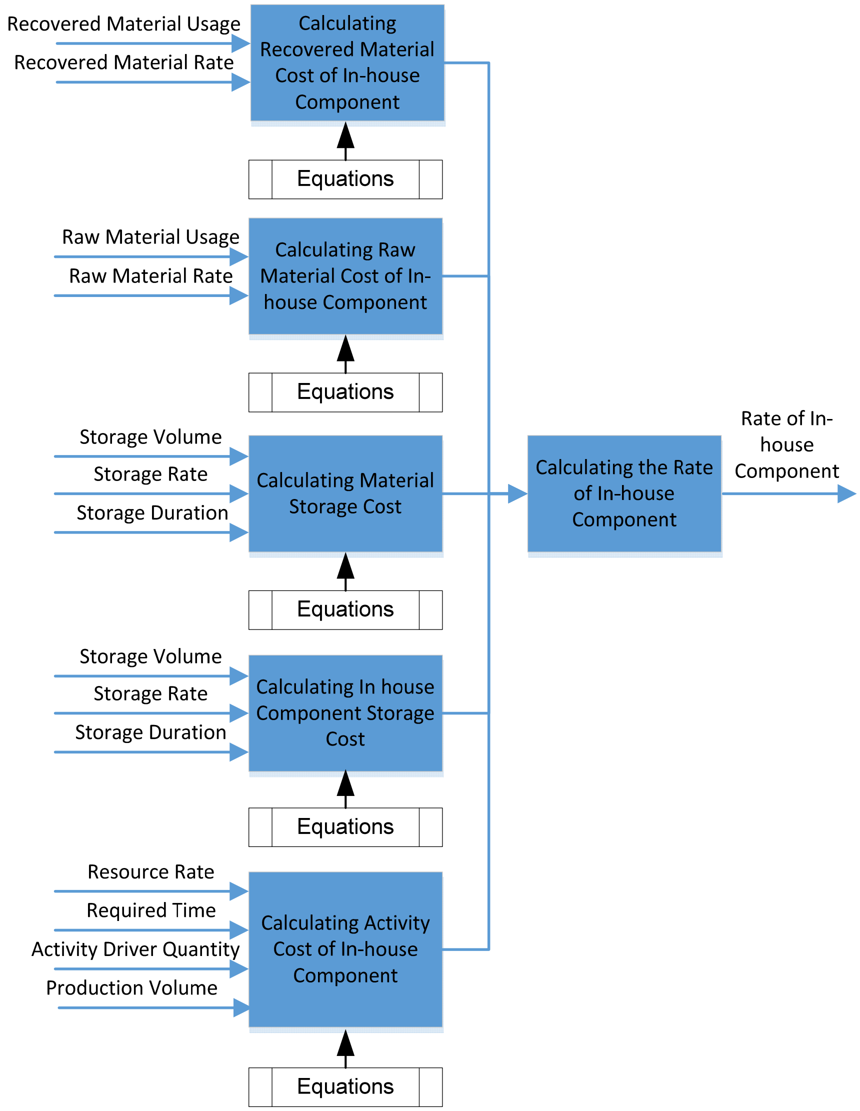

Figure 4.33. Calculating the Rate of In-house Component

The recovered material cost of the in-house component is calculated by multiplying the material usage and the rate of the recovered material of the in-house component as shown in Equation 4.49. The material usage of the recovered material is the multiplication of the usage percentage of the recovered material with the weight of the in-house component as shown in Equation 4.50. As the recovered material is always bulk material, the usage percentage of each recovered material is calculated by dividing the total weight of the recovered material with the total weight of all components that use the bulk material as shown in Equation 4.51.

$$\boldsymbol{RMC = RRM \times RMU} \qquad \text{Equation 4.49}$$

$$\boldsymbol{RMU = \%RM \times WC} \qquad \text{Equation 4.50}$$

$$\%\boldsymbol{RM} = \frac{\boldsymbol{TRMW}}{(\boldsymbol{TPWM+TRMW})} \quad \text{Equation 4.51}$$

Similar to the recovered material, the raw material cost of the in-house component is calculated by multiplying the material usage and the rate of the raw material of the in-house component as shown in Equation 4.52. The rate of the raw material is calculated or taken from the inputted parameters. The raw material of the in-house component is characterised by its material and shape. Therefore the raw material cost is calculated for each material and shape. For the bulk material, the percentage of the raw material is taken from Equation 4.51. For the material instead of bulk material, the percentage of the raw material is zero. The material usage of the raw material is the multiplication of the usage percentage of the raw material with the weight of the in-house component as shown in Equation 4.53. The percentage of the raw material is one hundred per cent minus the percentage of the recovered material.

$$\boldsymbol{MC} = \boldsymbol{RM} \times \boldsymbol{MU} \quad \text{Equation 4.52}$$

$$\boldsymbol{MU} = (\boldsymbol{1} - \%\boldsymbol{RM}) \times \boldsymbol{WC} \quad \text{Equation 4.53}$$

The storage cost is calculated by multiplying the storage volume with the storage rate and the storage duration as shown in Equation 4.54. The storage rate and the storage duration are calculated or taken from the inputted parameters. The storage volume of the material of the in-house component can be calculated by dividing the weight with the material density of the in-house component as shown in Equation 4.55. The storage volume of the in-house component is calculated with Equation 4.56 or Equation 4.57.

$$\boldsymbol{SC} = \boldsymbol{SV} \times \boldsymbol{SR} \times \boldsymbol{SD} \quad \text{Equation 4.54}$$

$$\boldsymbol{SV_{Material}} = \frac{\boldsymbol{WC}}{\boldsymbol{\rho}} \quad \text{Equation 4.55}$$

$$\boldsymbol{SV_{Box\ Component}} = \boldsymbol{L} \times \boldsymbol{W} \times \boldsymbol{H} \quad \text{Equation 4.56}$$

$$\boldsymbol{SV_{Cylinder\ Component}} = \frac{\boldsymbol{1}}{\boldsymbol{4}} \times \boldsymbol{\pi} \times \boldsymbol{D^2} \times \boldsymbol{L} \quad \text{Equation 4.57}$$

Then, the component activity cost of the in-house component is calculated by dividing the total activity cost with the production volume of the in-house component as shown in Equation 4.58. The component activity cost of the in-house component is calculated for both the general and manufacturing process activity of the in-house component. In addition, the component activity cost of the in-house component is also calculated for both the main shape and the additional feature of the in-house component. The total activity cost for the in-house component is the summation of resource cost of all activities consumed by the in-house component as shown in Equation 4.45. The resource cost of each activity is calculated by multiplying the required resource rate for each department with the total time usage of each activity as shown in Equation 4.44. The total time usage of each activity is calculated by multiplying the activity driver quantity and the required times to perform the activity for the in-house component as shown in Equation 4.43.

$$\boldsymbol{ICAC} = \frac{\boldsymbol{TAC}}{\boldsymbol{PVIC}} \qquad \text{Equation 4.58}$$

Finally, the rate of the in-house component is calculated by summing the recovered material cost, the raw material cost, the material storage cost, the component storage cost, and the component activity cost as shown in Equation 4.59.

$$\boldsymbol{RIC} = \boldsymbol{RMC} + \boldsymbol{MC} + \boldsymbol{SC}_{\boldsymbol{Material}} + \boldsymbol{SC}_{\boldsymbol{Component}} + \boldsymbol{ICAC} \qquad \text{Equation 4.59}$$

The steps to calculate the rate of an outsourced component ($/unit) are shown in Figure 4.34. First, the system calculates the storage cost of the outsourced component. Then, the cost of all activities consumed by the outsourced component is calculated. Finally, the system calculates the rate of the in-house component.

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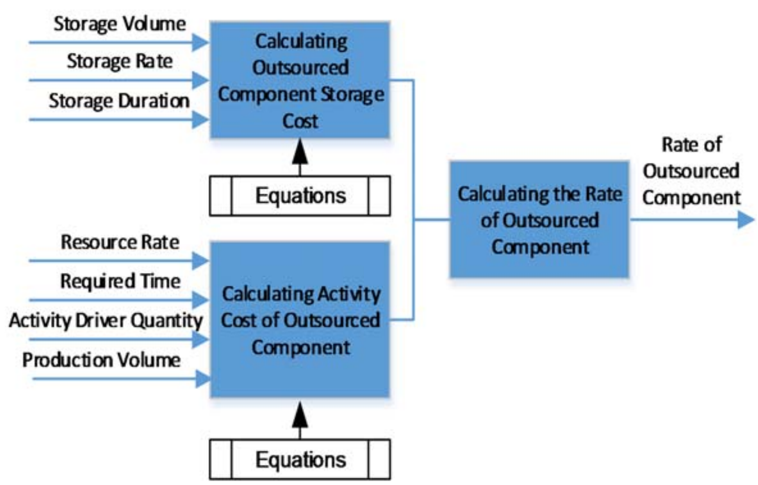

Figure 4.34. Calculating the Rate of Outsourced Component

The storage cost is calculated by multiplying the storage volume with the storage rate and the storage duration as shown in Equation 4.54. The storage rate and the storage duration are calculated or taken from the inputted parameters. The storage volume of the outsourced component is calculated with Equation 4.56 or Equation 4.57Then, the outsourced component activity cost is calculated by dividing the total activity cost with the purchased quantity of the outsourced component as shown in Equation 4.60. The total activity cost for the outsourced component is the summation of resource cost of all activities consumed by the outsourced component as shown in Equation 4.45. The resource cost of each activity is calculated by multiplying the required resource rate for each department with the total time usage of each activity as shown in Equation 4.44. The total time usage of each activity is calculated by multiplying the activity driver quantity and the required times to perform the activity for the outsourced component as shown in Equation 4.43.

$$\boldsymbol{OCAC = \frac{TAC}{TPQOC}} \quad \text{Equation 4.60}$$

Finally, the rate of outsourced component is calculated by summing the component storage cost, the outsourced component activity cost, and the outsourced component cost as shown in Equation 4.61.

$$\boldsymbol{ROC = SC_{Component} + OCAC + OCC} \quad \text{Equation 4.61}$$

4.10.4 Calculating Product Platform Rate

Figure 4.35 shows the steps how the system calculates the rate of a product platform ($/unit). First, the unrecovered component cost used by the product platform is calculated. Second, the recovered sub module cost used by the product platform is calculated. Then, the sub module cost used by the product platform is calculated. After that, the system calculates the storage cost of the product platform. Then, the cost of all activities consumed by the product platform is calculated. Finally, the system calculates the rate of the product platform.

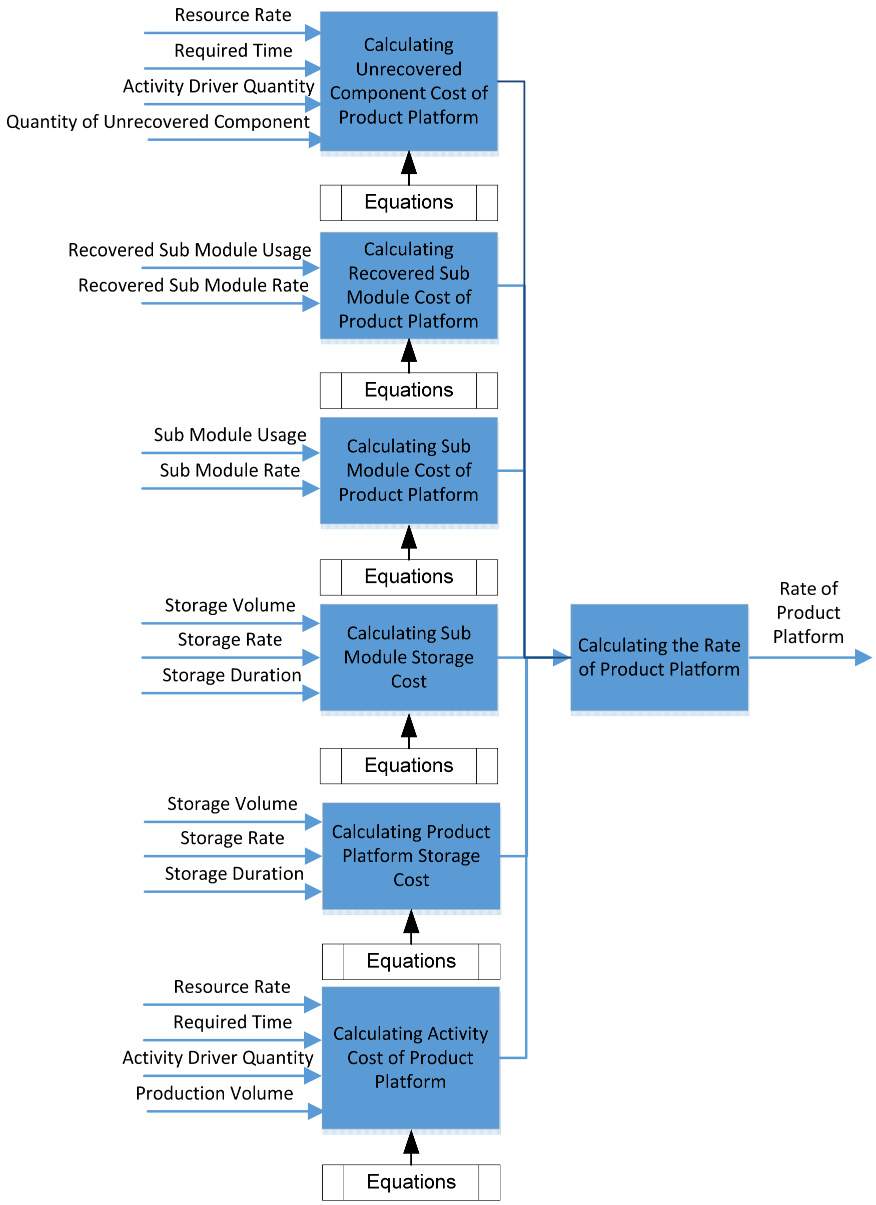

Figure 4.35. Calculating the Rate of Product Platform

As shown in Equation 4.62, the unrecovered component cost is calculated by dividing the summation of the total activity cost and the taken back cost for the unrecovered component by the total quantity of the unrecovered component and then multiply the result by the quantity of the component used in the product platform.

$$UCC = \frac{TAC+TBC}{QCRM} xQC \qquad \text{Equation 4.62}$$

The recovered sub module cost of the product platform is calculated by multiplying the usage and the rate of the recovered sub module as shown in Equation 4.63. The usage of the recovered sub module is the multiplication of its usage percentage with the quantity of the sub module required by the product platform as shown in Equation 4.64. The usage percentage of each recovered sub module is calculated by dividing the total quantity of the recovered sub module with the total quantity of the sub module required by all product variants as shown in Equation 4.65.

$$\boldsymbol{RSC} = \boldsymbol{RRS} \times \boldsymbol{RSU} \qquad \text{Equation 4.63}$$

$$\boldsymbol{RSU}_{\boldsymbol{Product\ Platform}} = \%\boldsymbol{RS} \times \sum\nolimits_{\boldsymbol{Product\ Variant\ in\ the\ same\ Product\ Family}}(\boldsymbol{PV} \times \sum\nolimits_{\boldsymbol{module}}(\boldsymbol{QM} \times \sum\nolimits_{\boldsymbol{Sub\ Module}}(\boldsymbol{QSM}))) \qquad \text{Equation 4.64}$$

$$\%\boldsymbol{RS} = \frac{\boldsymbol{QRSM}}{\sum_{\boldsymbol{Product\ Variant}}(\boldsymbol{PV} \times \sum_{\boldsymbol{Module}}(\boldsymbol{QM} \times \sum_{\boldsymbol{Sub\ Module}}(\boldsymbol{QSM})))} \qquad \text{Equation 4.65}$$

To calculate the sub module cost, the usage of the sub module is multiplied with the sub module rate as shown in Equation 4.66. The rate of the sub module is calculated or taken from the inputted parameters. The usage of the sub module is the multiplication of the usage percentage of the sub module with the quantity of the sub module required by the product platform as shown in Equation 4.67. The percentage of the sub module is one hundred per cent minus the percentage of the recovered sub module.

$$\boldsymbol{SMC} = \boldsymbol{RSM} \times \boldsymbol{SMU} \qquad \text{Equation 4.66}$$

$$\boldsymbol{SMU}_{\boldsymbol{Product\ Platform}} = (\boldsymbol{1} - \%\boldsymbol{RS}) \times \sum\nolimits_{\boldsymbol{Product\ Variant\ in\ the\ same\ Product\ Family}}(\boldsymbol{PV} \times \sum\nolimits_{\boldsymbol{module}}(\boldsymbol{QM} \times \sum\nolimits_{\boldsymbol{Sub\ Module}}(\boldsymbol{QSM}))) \qquad \text{Equation 4.67}$$

The product platform storage cost is calculated by multiplying the storage volume of the product platform with the storage rate and the product platform storage duration as shown in Equation 4.54. The storage volume of the product platform can be calculated by summing the storage volume of all sub modules of the product platform as shown in Equation 4.68. The storage volume of the sub module is calculated by summing the volume of all components of the sub module as shown in Equation 4.69. The storage cost for the sub module of product platform can be calculated with the same equation as the product platform storage cost.

$$SV_{Product\ Platform} = \sum_{Product\ Variant\ in\ the\ same\ Product\ Family}(PV \times \sum_{module}(QM \times QSM) \times SV_{Sub\ Module})$$ Equation 4.68

$$SV_{Sub\ Module} = \sum_{Component\ of\ Sub\ Module}(QC \times SV_{Component})$$ Equation 4.69

Then, the activity cost of the product platform is calculated by dividing the total activity cost with the production volume of the product platform as shown in Equation 4.70. The production volume of the product platform is the summation of the production volume of all product variants that require the same product platform. The total activity cost for the product platform is the summation of the resource cost of all activities consumed by the product platform as shown in Equation 4.45. The resource cost of each activity is calculated by multiplying the required resource rate for each department with the total time usage of each activity as shown in Equation 4.44. The total time usage of each activity is calculated by multiplying the activity driver quantity and the required times to perform the activity for the product platform as shown in Equation 4.43. The component activity cost of the product platform is calculated for both its general and assembly process activity.

$$PPAC = \frac{TAC}{\sum_{Product\ Variant\ in\ the\ same\ Product\ Family}(PV)}$$ Equation 4.70

The rate of the product platform is calculated by summing the cost of all unrecovered components used by the product platform, the cost of all recovered sub modules used by the product platform, the cost of all sub modules used by the product platform, the product platform storage cost, the sub module of product platform storage cost, and the product platform activity cost as shown in Equation 4.71.

$$RPP = UCC + RSC + SMC + SC_{Product\ Platform} + SC_{Sub\ Module} + PPAC$$ Equation 4.71

4.10.5 Calculating Product Variant Rate

The steps to calculate the rate of a product variant ($/unit) are shown in Figure 4.36. First, the unrecovered component cost used by the variant is calculated. Second, the recovered sub module cost used by the variant is calculated. Then, the sub module cost used by the variant is calculated. After that, the system calculates the storage cost of the variant and taken back product. The activities cost consumed by the taken back product is then calculated. Next, the cost of all activities consumed by the variant and the product variant are calculated. Finally, the system calculates the rate of the product variant.

The unrecovered component cost for the variant is calculated by dividing the total activity cost for the unrecovered component by the total quantity of unrecovered component and then multiplying the result by the quantity of the component used in the variant as shown in Equation 4.62.

The recovered sub module cost of the variant is calculated by multiplying the usage and the rate of the recovered sub module as shown in Equation 4.63. The usage of the recovered sub module is the multiplication of the usage percentage of the recovered sub module with the quantity of the sub module required by the variant as shown in Equation 4.72. The usage percentage of each recovered sub module is calculated by dividing the total quantity of the recovered sub module with the total quantity of the sub module required by all product variants as shown in Equation 4.65.

$$\boldsymbol{RSU}_{\boldsymbol{Variant}} = \%\boldsymbol{RS} \times (\boldsymbol{PV} \times \textstyle\sum_{\boldsymbol{module}}(\boldsymbol{QM} \times \sum_{\boldsymbol{Sub\ Module}}(\boldsymbol{QSM}))) \qquad \text{Equation 4.72}$$

To calculate the sub module cost of the variant, the usage of the sub module is multiplied with the sub module rate as shown in Equation 4.66. The usage of the sub module is the multiplication of the usage percentage of the sub module with the quantity of the sub module required by the variant as shown in Equation 4.73. The percentage of the sub module is one hundred per cent minus the percentage of the recovered sub module.

$$\boldsymbol{SMU}_{\boldsymbol{Variant}} = (\mathbf{1} - \%\boldsymbol{RS}) \times (\boldsymbol{PV} \times \textstyle\sum_{\boldsymbol{module}}(\boldsymbol{QM} \times \sum_{\boldsymbol{Sub\ Module}}(\boldsymbol{QSM}))) \qquad \text{Equation 4.73}$$

The variant storage cost is calculated by multiplying the storage volume of the variant with the storage rate and the variant storage duration as shown in Equation 4.54. The storage volume of the variant can be calculated by summing the storage volume of all sub modules of the variant as shown in Equation 4.74. The storage volume of the sub module of the variant is calculated by summing the volume of all components of the sub module required by the variant as shown in Equation 4.69. The storage cost for the sub module of variant can be calculated with the same equation as the variant storage cost.

$$\boldsymbol{SV}_{\boldsymbol{Variant}} = \boldsymbol{PV} \times \textstyle\sum_{\boldsymbol{module}}(\boldsymbol{QM} \times \boldsymbol{QSM}) \times \boldsymbol{SV}_{\boldsymbol{Sub\ Module}} \qquad \text{Equation 4.74}$$

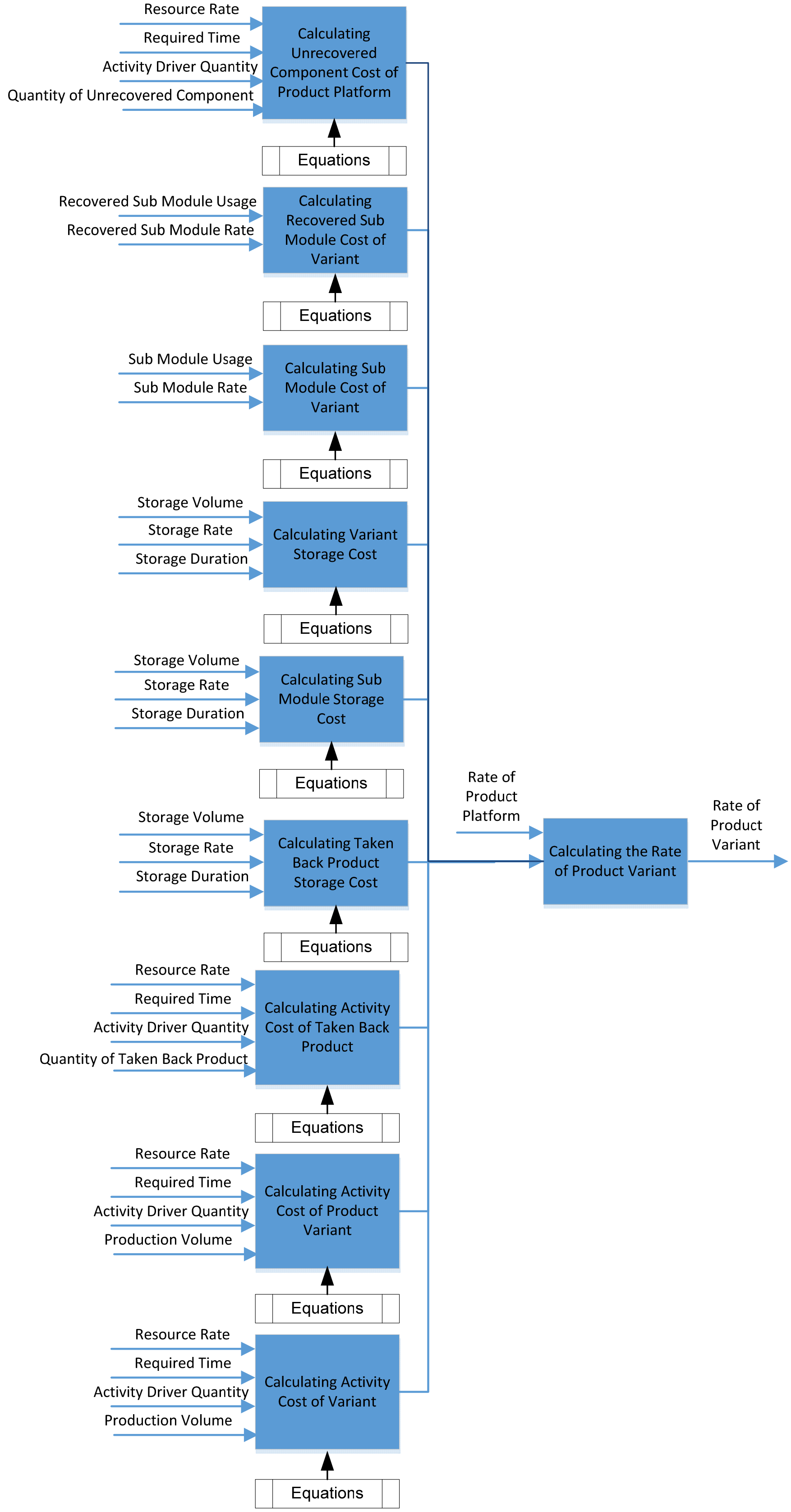

Figure 4.36. Calculating the Rate of Product Variant

The activity cost of the taken back product is calculated by dividing the total activity cost with the quantity of the taken back product as shown in Equation 4.75. The total activity cost for taken back product is the summation of the resource cost of all activities consumed by the taken back product as shown in Equation 4.45. The resource cost of each activity is calculated by multiplying the required resource rate for each department with the total time usage of each activity as shown in Equation 4.44. The total time usage of each activity is calculated by multiplying the activity driver quantity and the required times to perform the activity for the taken back product as shown in Equation 4.43. The activity cost of the taken back product is calculated for both its general and disassembly process activity.

$$\boldsymbol{TBPAC = \frac{TAC}{\%A \times PV}}$$ Equation 4.75

The taken back product storage cost is calculated by multiplying the storage volume of the taken back product with the storage rate and the variant storage duration as shown in Equation 4.54. The storage volume of the taken back product can be calculated by summing the storage volume of product platform and variant as shown in Equation 4.76.

$$\boldsymbol{SV_{Taken\ Back\ Product} = SV_{Product\ Platform} + SV_{Variant}}$$ Equation 4.76

The activity cost of the variant is calculated by dividing the total activity cost with the production volume of the product variant as shown in Equation 4.77. The total activity cost for the variant is the summation of resource cost of all activities consumed by the variant as shown in Equation 4.45. The resource cost of each activity is calculated by multiplying the required resource rate for each department with the total time usage of each activity as shown in Equation 4.44. The total time usage of each activity is calculated by multiplying the activity driver quantity and the required times to perform the activity for the variant as shown in Equation 4.43. The component activity cost of the variant is calculated only for the assembly process activity of the variant.

$$\boldsymbol{VAC = \frac{TAC}{PV}}$$ Equation 4.77

Then, the activity cost of the product variant is calculated by dividing the total activity cost with the production volume of the product variant as shown in Equation 4.78. The total activity cost for the product variant is the summation of the resource cost of all activities consumed by the product variant as shown in Equation 4.45. The resource cost of each activity is calculated by multiplying the required resource rate for each department with the total time usage of each activity as shown in Equation 4.44. The total time usage of each activity is calculated by multiplying the activity driver quantity and the required times to perform the activity for the product variant as shown in Equation 4.43. The component activity cost of the product variant is calculated only for the general process activity of the product variant.

$$\boldsymbol{PVAC = \frac{TAC}{PV}} \qquad \text{Equation 4.78}$$

The rate of product variant is calculated by summing the cost of all unrecovered components used by the variant, the cost of all recovered sub modules used by the variant, the cost of all sub modules used by the variant, the storage cost of the variant and its sub modules, the taken back product activity cost, the taken back product storage cost, the product variant activity cost, the variant activity cost, and the product platform rate as shown in Equation 4.79.

$$\boldsymbol{RPV = UCC + RSC + SMC + SC_{Variant} + SC_{Sub\ Module} + TBPAC + SC_{Taken\ Back\ Product} + VAC + PVAC + RPP} \qquad \text{Equation 4.79}$$

4.10.6 Calculating Life Cycle Cost

To estimate the life cycle cost of an in-house component, the cost of each activity consumed by the in-house component is categorised according to twenty cost component categories. The cost component categories are product development cost, product design cost, product evaluation cost, production planning cost, inventory control cost, procurement cost, manufacturing cost, material and component cost, assembly cost, packaging cost, quality control cost, inventory cost, marketing cost, sales cost, transportation cost, customer service cost, warranty cost, take back cost, end of life cost, and disassembly cost. In this research, the cost of raw material, the cost of component, and the cost of the sub module are categorised into the material and component cost. In addition, various storage costs are categorised into the inventory cost. Then the cost of each component category is categorised further according to four life cycle stages: research and development, production, after sales, and end of life. The life cycle cost of the in-house component is the cost of all in-house component activities that are performed in each life cycle stage.

Similar to the in-house component, the cost of each activity consumed by a product platform is categorised according to nineteen cost component categories in order to estimate the life cycle cost of the product platform. Then the cost of each component category is categorised further into four costs according to four life cycle stages. The cost of each life cycle stage is calculated by summing all activity costs categorised in the stage.

To estimate the life cycle cost of a product variant, the cost of each activity consumed by the variant and product variant is also categorised according to nineteen cost component categories. Then, the cost of each component category is categorised into four life cycle stages. The cost of each life cycle stage for product variant is calculated by summing all activity costs of the variant, the product variant, and the product platform that is categorised in the stage.

Chapter 5: Time-driven Life Cycle Cost Estimation System Prototype

Chapter 5 contains a description of the development of the time-driven life cycle cost estimation system prototype. The prototype of the time-driven life cycle cost estimation system, in the form of software, is developed in order to evaluate the applicability of the proposed system. Section 5.1 describes the development process of the prototype of the proposed system. This section explains each required stage to develop the system prototype from the definition of the requirement to the evaluation of the system prototype. Then, the user interface of the prototype of the time-driven life cycle cost estimation system is described further in Section 5.2.

After the time-driven life cycle cost estimation system prototype has been built, the evaluation process of the system prototype can be started. Before the evaluation process, the master databases must be completed by storing the required data. Section 5.3 describes the flow of work to store the data into the master databases. The data stored in the master database is the knowledge to generate the components with their attributes and to generate the activities and resources. In this section, the completion of the master databases is explained for each part of the system as already outlined in Section 4.1. First, the master databases for the first part of the system are completed to generate the components and their attributes. Then, the completion of the master databases for the second part to generate the activities and resources is explained. As the calculation of the life cycle cost does not require any master databases, no master database is built for the third part of the system.

After all required master databases are completed, the user can start to implement the system prototype by storing the required data into the transaction databases. The stored data in the transaction database is the input to generate the components with their attributes and generate the activities and resources. Section 5.4 explains each required step to enter the inputs to the transaction databases in order to estimate the life cycle cost of the product family at the early stage of product development. In this section, the completion of the transaction databases is also explained for each part of the system as already outlined in Section 4.1.

Finally, the process to evaluate the system prototype is explained in Section 5.5.

5.1 DEVELOPING THE SYSTEM PROTOTYPE

The development process of the prototype of the time-driven life cycle cost estimation system is adapted from several models proposed by various studies in literature (Mohapatra, 2010; Royce, 1970; Schmidt, 2013). The stages required to develop the system prototype is shown in Figure 5.1, which are the requirement definition, system design, system build, and system evaluation stages.

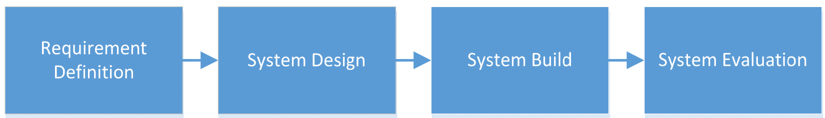

Figure 5.1. Developing Time-driven Life Cycle Cost Estimation System Prototype

The requirement of the prototype of the time-driven life cycle cost estimation system is defined, based on the aim this research. The system prototype must be able to transform the market segment, the production volume, the product family structure, and the product family function into the activities and resources consumed by each component level of a product family. Then, the system prototype must be able to allocate and calculate the life cycle cost of each component level of different product families.

Departing from the requirement, the next stage is to design the system prototype that can achieve the requirements above. First, the required databases, the required rules, the required equations, and the relationships among them are identified. Then, how the database, the rule, the equation, and their relationships should be built is designed.

The next stage covers all the processes to build the system prototype. This stage consists of the build of the databases, the rules, the equations, the relationships among database, rule, and equation, and the user interfaces. MySQL Community Edition is used to build the database and all relationships with database. Visual Studio Community 2013 is used to build the rule, the equation, all relationships with the rule and the equation, and the user interface. The tools to build the system prototype are chosen because they are widely used, free, and compatible to each other. The user interface of the prototype of the time-driven life cycle cost estimation system is described further in Section 5.2. However, the detailed process to build the system prototype is not presented in this report because it is too technical and out of the scope of this research.

As described in Chapter 4, the time-driven life cycle cost estimation system requires a certain number of databases, rules, and equations. The required databases can be categorised into master and transaction databases. The master databases, the rules, and the equations are used to represent, retain, and organise the required knowledge in order to generate the components with their attributes, generate the activities and resources, and calculate the life cycle cost. The transaction databases are used to store the required inputs in order to estimate the life cycle cost of a product family. The master databases, the rules, and the equations must be built before the transaction databases.

After the time-driven life cycle cost estimation system prototype has been built, the evaluation process of the system prototype can be started. To enable the evaluation process, the master and transaction databases must be completed by storing the required data. The data storage process of the master and transaction databases is described further in Sections 5.3 and 5.4 respectively.

The first purpose of the evaluation process is to evaluate the functionality of the system prototype that has been built. The functionality of the system prototype is evaluated by testing each menu of the system prototype as to whether it can provide the specified function or not. The second purpose of the system evaluation is to verify the result of the system prototype. This evaluation is performed by comparing the result of the system prototype against the manual process. The process to evaluate the system prototype is explained further in Section 5.5.

5.2 USER INTERFACE OF THE SYSTEM PROTOTYPE

In implementing the system prototype, the required steps to estimate the life cycle cost of each component level of a product family, as explained in Chapter 4, are categorised into eleven step categories. These steps are categorised based on the required outputs of the system. The step categories and the required outputs of each step are shown in Table 5.1. Before conducting the first step, several parameters as outlined in Section 4.10 need to be defined as explained in Section 4.10. Therefore, the system prototype has twelve menus on the menu bar, as shown in Figure 5.2.

When the menu is clicked, the pull-down menu contains several submenus that will be displayed. The submenu in the master database category is used to add, modify, delete, or find the data in the master databases for the related menu. To add, modify, delete, or find the data in the transaction databases, the submenu in the transaction database category must be clicked. In addition, the submenu in the reports category is used to generate the related report.

Table 5.1. Steps and Their Outputs

Step	Output
I	Product Family and Their Product Variants Product Variant and Their Attributes Modules of each Product Variant
II	Selected Sub Module Options of each Module
III	Components of each Selected Sub Module Option
IV	Attributes of each In-house Component Attributes of each Additional Feature of In-house Component
V	Selected Assembly Methods for each Assembly Sequence of Product Platform Selected Assembly Methods for each Assembly Sequence of Product Variant Selected Joining Processes for each Assembly Sequence of Product Platform Selected Joining Processes for each Assembly Sequence of Product Variant
VI	Quantity of Recovered Sub Module for each End of Life Strategy Total Quantity of each Recovered Sub Module Total Weight of each Recovered Material
VII	Selected Manufacturing Process Chain for each In-house Component Selected Manufacturing Process Chain for each Additional Feature of In-house Component
VIII	Selected Outsourcing Process of each Outsourced Component
IX	Selected Outsourcing Process of each Raw Material
X	Activities and Resources Consumed by each Component Activities and Resources Consumed by each Additional Feature of Component Activities and Resources Consumed by each Product Platform Activities and Resources Consumed by each Product Variant Activities and Resources Consumed by each Taken Back Product Variant Activities and Resources Consumed by each Recovered Sub Module Activities and Resources Consumed by each Recovered Material
XI	Rate of each Recovered Material Rate of each Recovered Sub Module Rate of each Component Rate of each Product Platform Rate of each Product Variant Cost for each Category of Component Cost for each Category of Product Platform Cost for each Category of Variant Life Cycle Cost of each Component Life Cycle Cost of each Product Platform Life Cycle Cost of each Product Variant

The Parameters menu is used to store the value of various operational, quality, inventory, market, financial, and end of life parameters. Therefore, the Parameters menu consists of operational, quality, inventory, market, financial, and end of life sub menus as shown in Figure 5.3. Each submenu of the Parameters menu is used to add, modify, or delete the value of its related parameters.

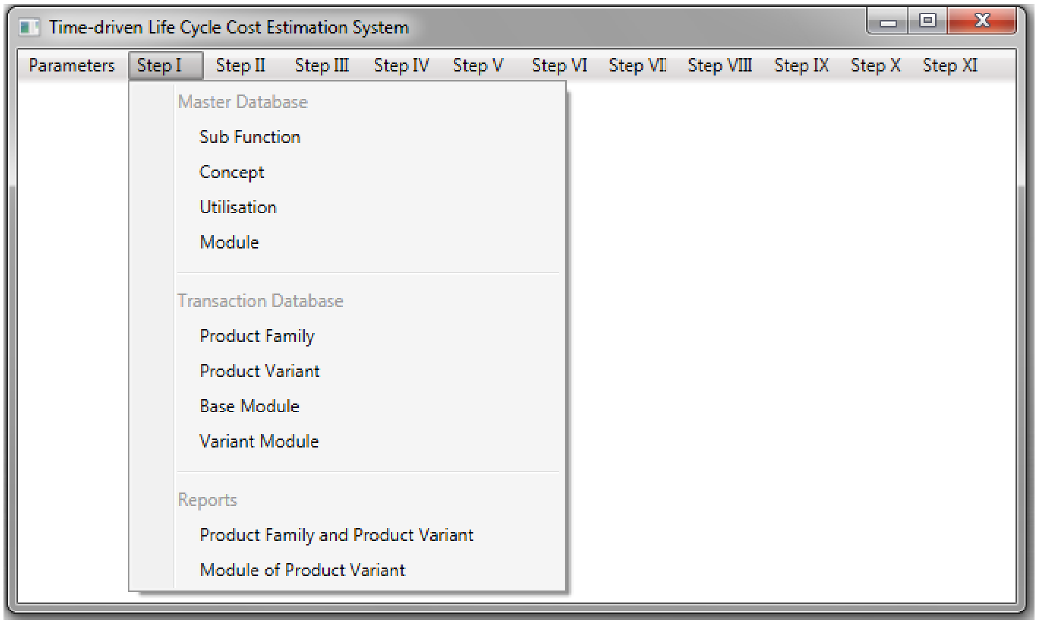

Figure 5.2. User Interface of Time-driven Life Cycle Cost Estimation System Prototype

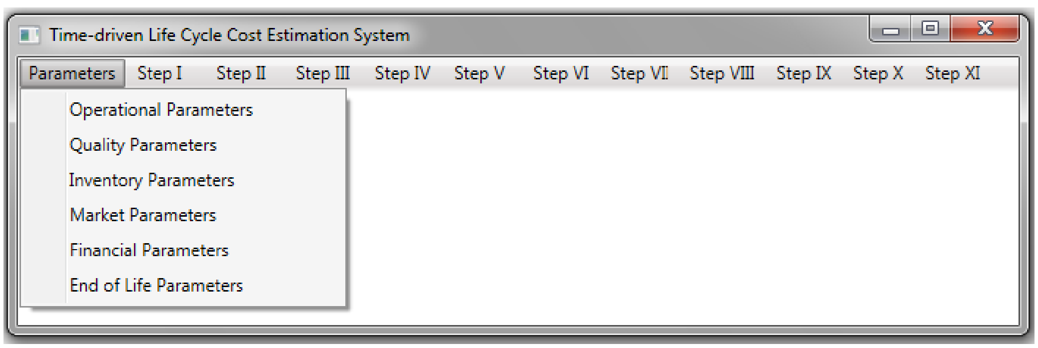

Figure 5.3. Sub Menu of Parameters

Step I menu is used to store various sub functions, various concepts of each sub function, various utilisations, and various modules into the master databases as shown in Figure 5.2. This menu also is used to input the product family that is developed, the product variant of each product family with its attributes, the base module of the product family, and the variant module of each product variant into the transaction databases. After the data storage process, the reports related to the product family with its product variant and the module of each product variant can be generated.

Figure 5.4 shows various submenus of Step II. The submenus in the master database category are used to store various sub modules with their attributes, various materials and their attributes, various sub module options for each sub module, and various sub modules of each module with their quantity. The submenus in the transaction category are used to select the sub module option for each base and variant module of the product family. The report submenu can be used to generate the selected sub module option for each module of the product family.

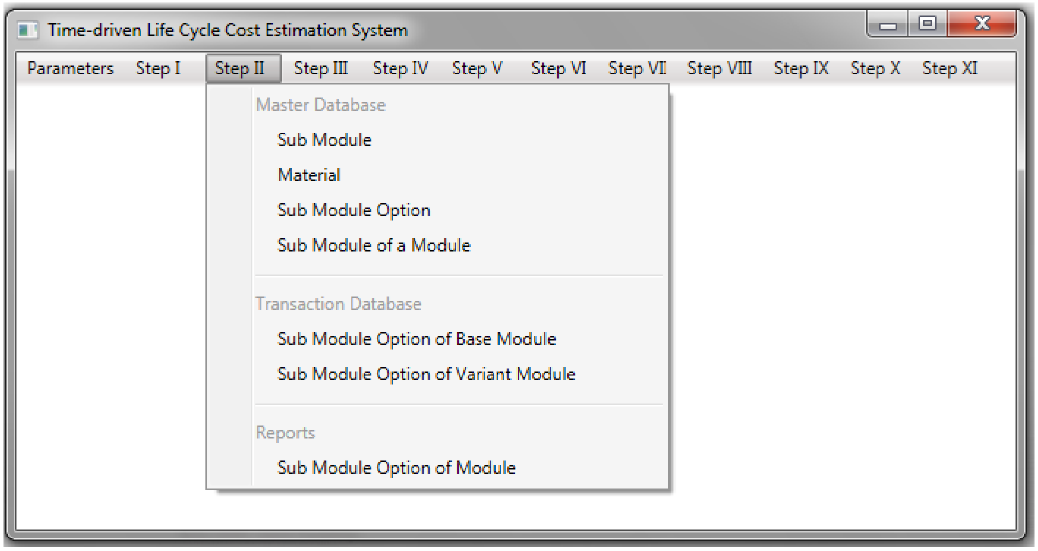

Figure 5.4. Sub Menu of Step II

The submenus in the master database of Step III, as shown in Figure 5.5, are used to store various components with their attributes and various components of each sub module option with their quantity. Step III menu does not have a submenu in the transaction database category because no input is required for this step. The report submenu of Step III can be used to generate the component of the selected sub module option for each module of the product family.

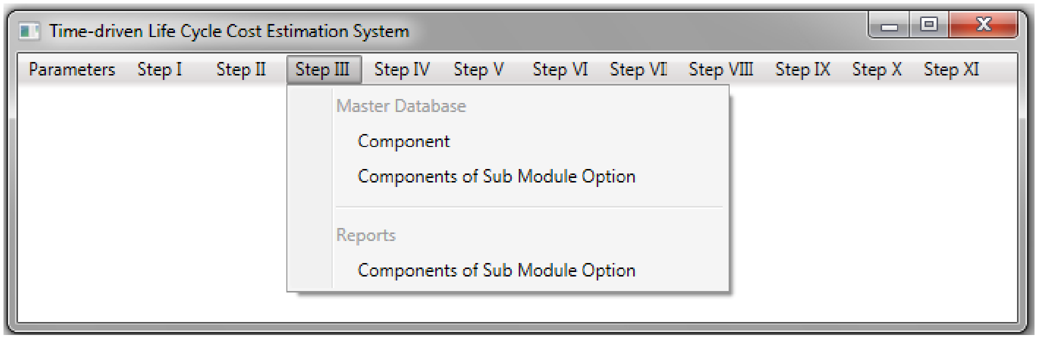

Figure 5.5. Sub Menu of Step III

Figure 5.6 shows that submenus in the master database category of Step IV are used to store various basic shapes, various shape complexities, various required material properties, various required surface finishes, various in-house components with their attributes, various surface finishes of each in-house component, various additional features of each in-house component with their attributes, and various surface finish of each additional feature. The report submenus of Step IV can be used to generate the in-house components with their attributes including their additional features.

The submenus in the master database of Step V, as shown in Figure 5.7, are used to store various processes, various assembly methods, joining processes, and disassembling processes. Step V submenus in the transaction database category are used to define the assembly sequence and select the joining process for each product platform and each product variant. The report submenus of Step V can be used to generate the assembly method and joining process for product platform and product variant.

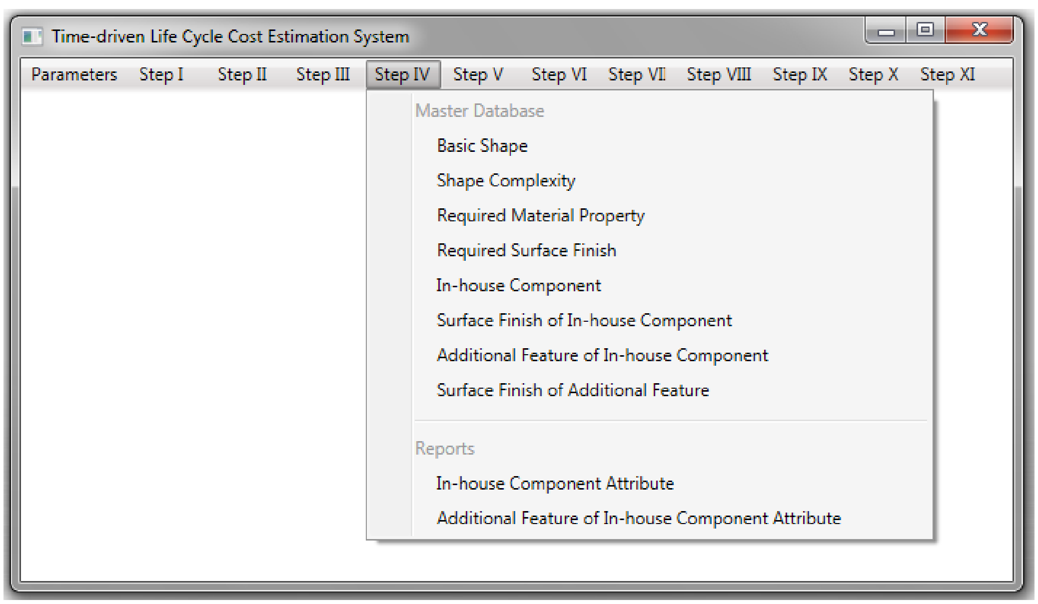

Figure 5.6. Sub Menu of Step IV

The report submenus of Step VI are used to generate the quantity of recovered sub module option and recovered material. Figure 5.8 shows that there is no submenu in the master and transaction database category of Step VI. It means that no required data needs to be stored in the master databases and transaction databases. The quantity of recovered sub module option and recovered material are generated, based on the previous inputs.

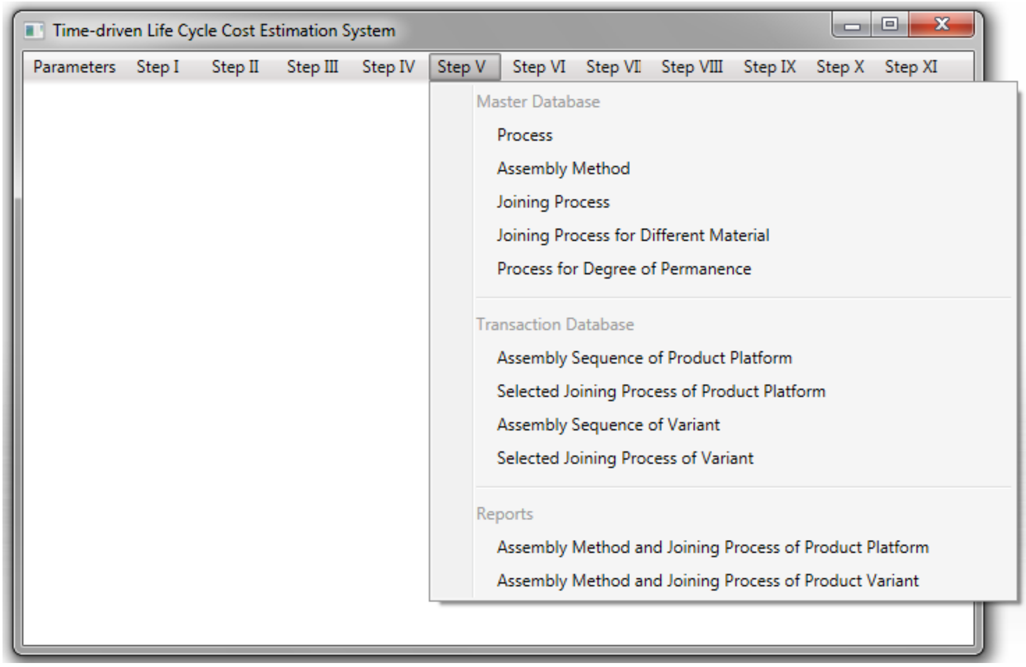

Figure 5.7. Sub Menu of Step V

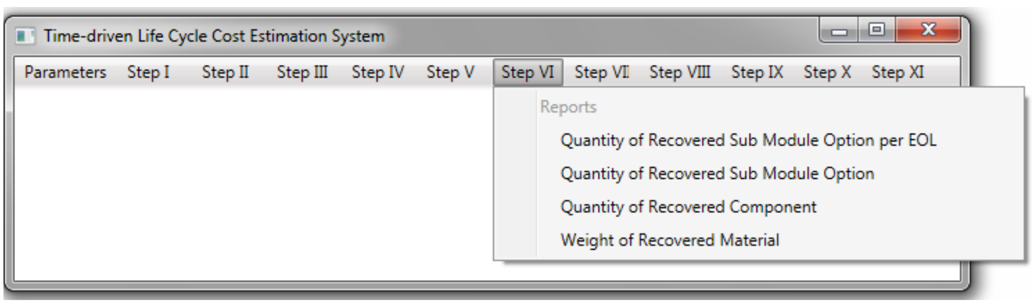

Figure 5.8. Sub Menu of Step VI

Submenus in the master database category of Step VII, as shown in Figure 5.9, are used to store various manufacturing processes for various materials, production volumes, basic shapes, shape complexities, raw material shapes, additional feature types, material properties, and surface finish requirements. In addition, one of the sub menus in the master database category is used to store various cleaning processes. The submenus are also used to store various constraints of the manufacturing process and various cleaning processes. The submenus in the transaction database category are used to select one of the required manufacturing processes and the cleaning processes that are going to be implemented. When the selected manufacturing process is no longer required, then the delete transaction submenu can be used to delete the manufacturing process. Finally, the report submenus can be used to generate all selected manufacturing processes and cleaning processes for the in-house component and its additional feature.

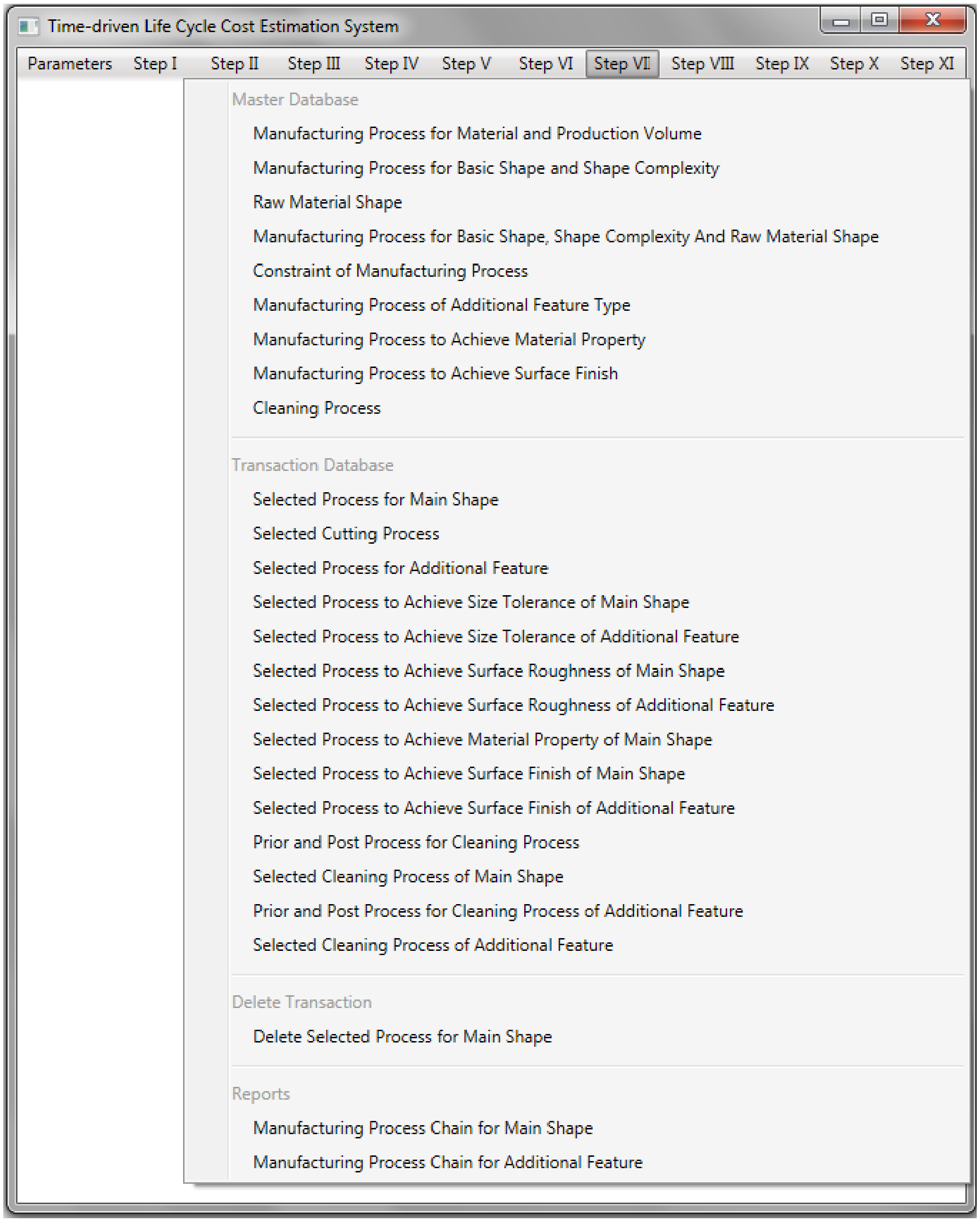

Figure 5.9. Sub Menu of Step VII

The submenus in the master database of Step VIII, as shown in Figure 5.10, are used to store various suppliers with their region and various outsourcing processes for each outsourced component. Step VIII submenu in the transaction database is used to select the outsourcing process for each outsourced component. The report submenu of Step VIII can be used to generate the outsourcing process for each outsourced components.

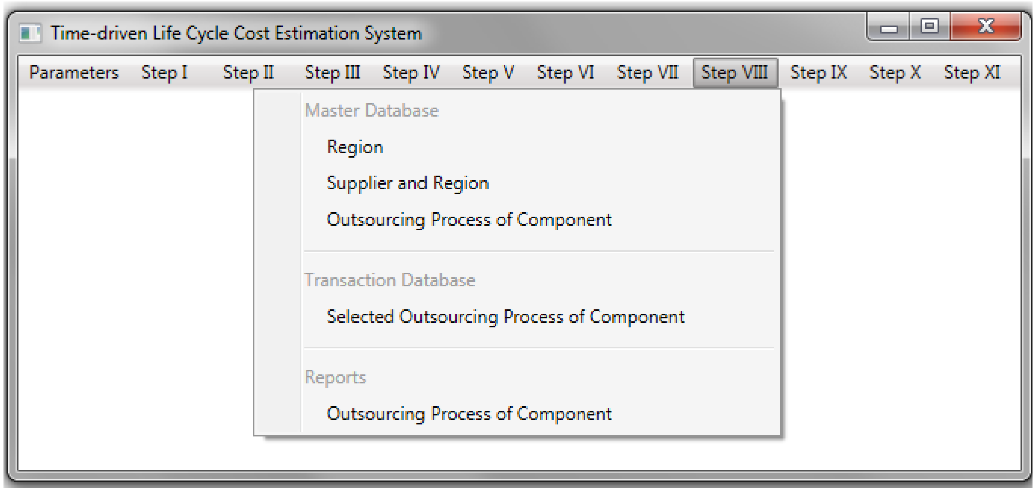

Figure 5.10. Sub Menu of Step VIII

The submenus in the master database of Step IX, as shown in Figure 5.11, are used to store various outsourcing processes for each raw material. Step IX submenu in the transaction database is used to select the outsourcing processes for each raw material. The report submenu of Step IX can be used to generate the required weight and the outsourcing processes for each raw material.

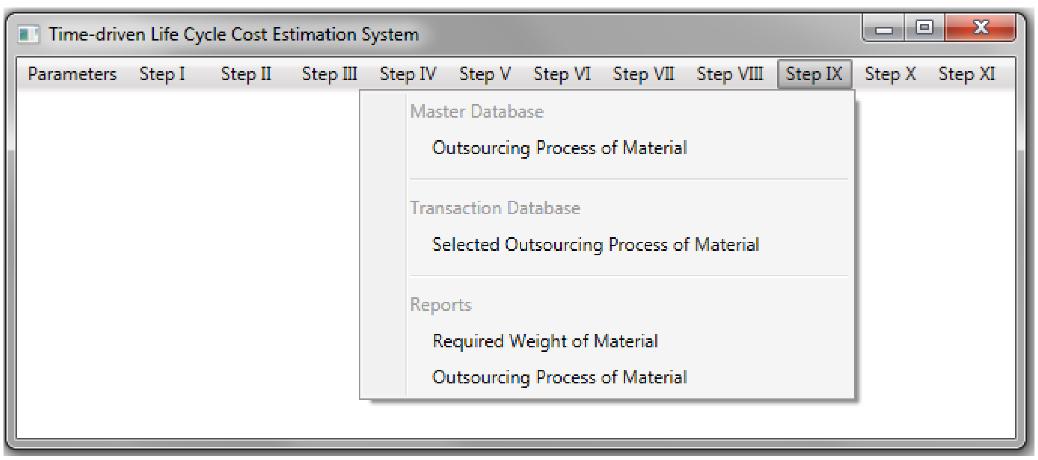

Figure 5.11. Sub Menu of Step IX

Figure 5.12 shows that the submenus in the master database of Step X are used to store various departments, activities, activity categories, activity drivers, and the required time for each activity. It also shows that there is no submenu in the transaction database category of Step X. It means that no required input is required for transaction databases. The submenus in the report category are used to generate the activities for each component, each additional feature of the component, each product platform, each product variant, each taken back product, each recovered sub module, and each recovered material based on the previous input.

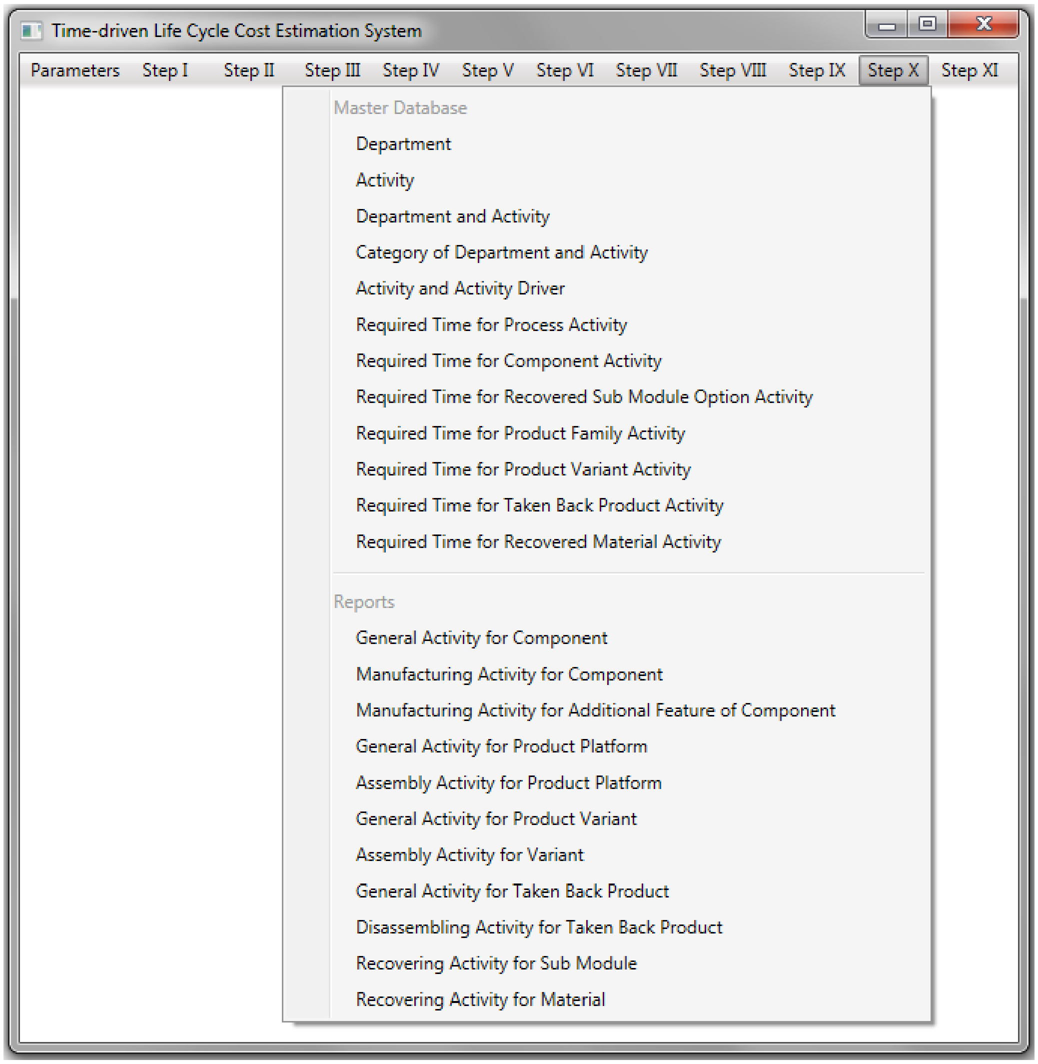

Figure 5.12. Sub Menu of Step X

The report submenu of Step XI, as shown in Figure 5.13, can be used to generate the rate of each recovered material, each recovered sub module, each component, each product platform, and each product variant. In addition, the submenus can also generate the cost of each category and the life cycle cost of each component, each product platform, and each product variant.

5.3 STORING DATA INTO MASTER DATABASES

As explained above, the master databases are needed to represent, retain, and organise the knowledge. The required data needs to be stored into the master databases only once before the implementation of the proposed system. However, the required data must be able to be modified and updated at any time. The person in charge, who collects and stores the required data into the master databases, could be the related expert or the user.

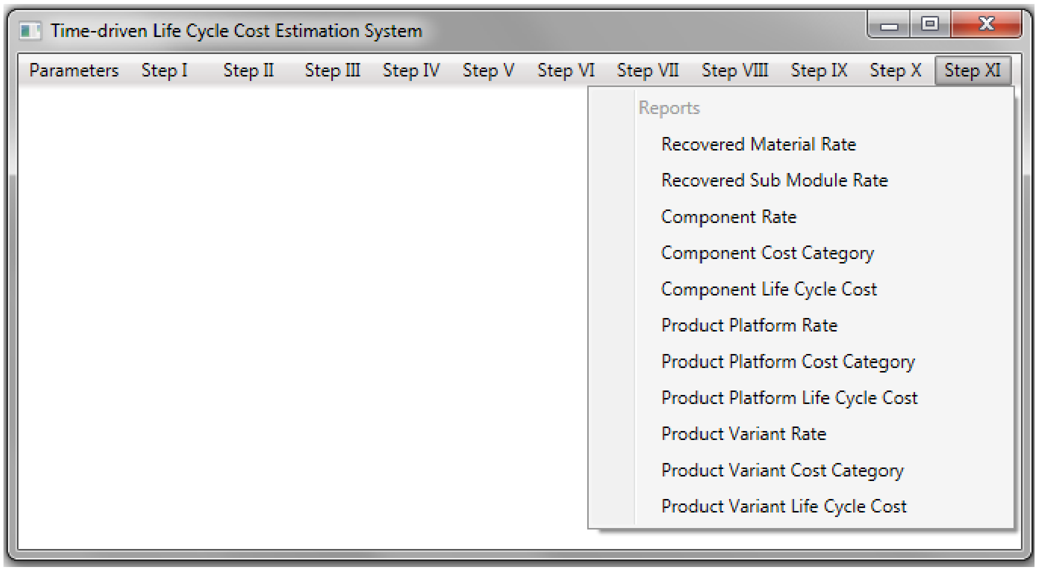

Figure 5.13. Sub Menu of Step XI

The steps to store the required data into the master databases are shown in Figure 5.14. First, all required data for the first part of the system, in order to generate the components and their attributes of the product family, are stored. The steps to store the required data into the master database for the first part of the system are described further in Section 5.3.1. Then, all required data to generate all activities and resources consumed by each component level of the product family are stored. The steps to store the required data into the master database for the second part of the system are described further in Section 5.3.2. The calculation of the life cycle cost of each component level of the product family does not require any master databases. Therefore, no step is required to store the required data in the master database for the last part of the system.

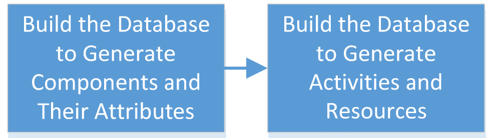

Figure 5.14. Storing Data into Master Database

5.3.1 Storing Data into Master Database for Components and Attributes Generation

The steps to store the required data into the master databases of the first part of the system in order to generate the components and their attributes of the product family are shown in Figure 5.15, Figure 5.17, Figure 5.18, and Figure 5.19. Before storing the required data into the required master databases, the person in charge of collecting and storing the required data needs to define the value of various operational, quality, inventory, market, financial, and end of life parameters. The parameters and their values are required to calculate the life cycle cost of the product family.

The first important master database in order to generate the components and their attributes is a module database. To store the required data into the module database, the person in charge is required to define various sub functions, concepts for each sub function, utilisations, and modules and their attributes as shown in Figure 5.15. The first step is to define various sub functions of various products that might be required by consumers. After the sub function is defined, various concepts that can be used to carry out each sub function are defined. Then, various utilisations of the product are defined. The utilisation option refers to various market segments that have common needs in term of product functionality. Figure 5.16 shows the example of the user interface to add, modify, delete, and find the sub function data in the master database.

After the sub functions, concepts, and utilisations have been defined, the person in charge can start to define various module and their attributes. As explained in the previous chapter, a module is a combination of subassembly and/or part of a product that is designed to carry out at least one sub function of the product. The module for each sub function is selected by considering their attributes such as the preferred concept, the utilisation, and other specific factors of the product variant that can distinguish one module from another module.

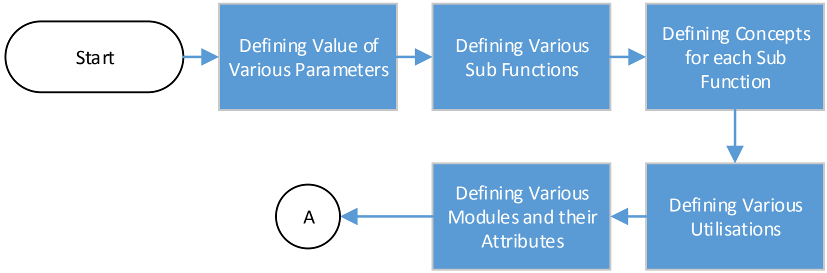

Figure 5.15. Storing data into Master Database to Generate Module

The next important master database required to generate the components and their attributes is a sub module database. To develop the sub module database, the person in charge is required to define various sub modules and their attributes, various materials and their attributes, various sub module options and their attributes, and various sub modules and their quantity for each module as shown in Figure 5.17.

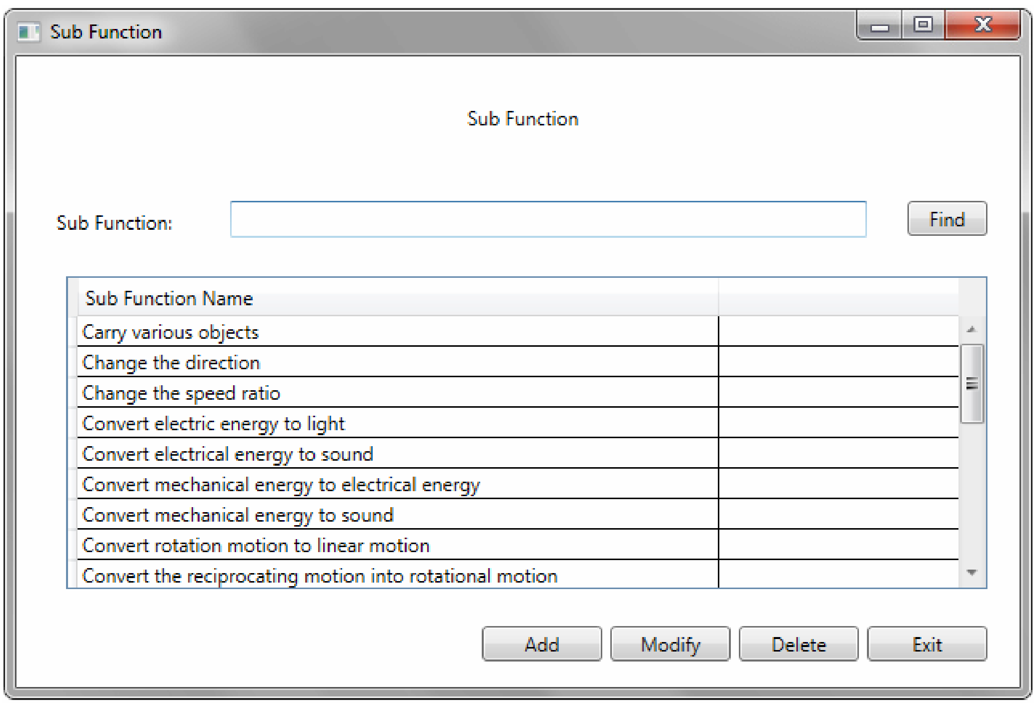

Figure 5.16. User Interface to Store Sub Function data into Master Database

The first step in developing the sub module database is to define various sub modules and their attributes. A sub module is a standardised and interchangeable sub assembly or part type of a component that can be independently produced or sold in the market. The only attribute of the sub module is its procurement strategy. The procurement strategy determines whether the sub module is manufactured in-house or outsourced to other party. The procurement strategy is already defined in the system. Therefore, the person in charge is not required to define them.

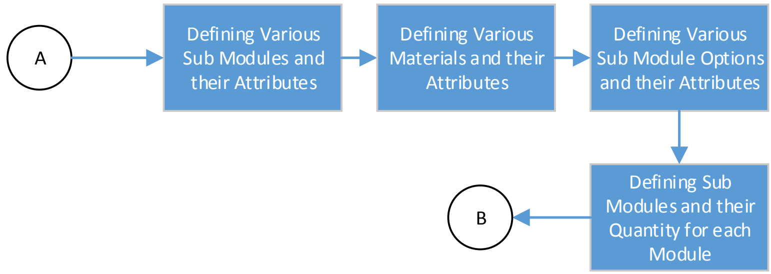

Figure 5.17. Storing data into Master Database to Generate Sub Module Option

The next step is to define various materials and their attributes. In order to define a new material, the person in charge is required to define the name, the density, the recovery complexity coefficient, and then select the end of life strategy of the material. An end of life strategy of a material is a strategy to reduce the bad impact of the material for the environment. The end of life strategy of material influences the end of life recovery process of the material that will be conducted for the non-reusable sub module.

Then, the person in charge needs to define various sub module option names, select the sub module that is related to each sub module option, and select the component type of each sub module option. A sub module option is one of the independently produced or sold sub modules selected to carry out the required sub function. The component type of the sub module option determines whether the sub module option is a sub assembly type or a part type of sub module.

After the modules and the sub modules are defined, the relationship between them needs to be defined. Each module consists of one or more sub modules. Therefore, first, the relationship determines the sub modules for each module. In addition, the quantity of the sub module for each module is also defined. The procurement strategy of the sub module is generated automatically by the system based on the defined attribute of the sub module. As various modules and sub modules are already defined, the person in charge is required to select a module name and a sub module name and then enter the quantity of the sub module to define the relationship between the sub module and the module.

After that, the person in charge needs to develop a component database. To develop the component database, the person in charge is required to define various components and their attributes and also the relationship between the component and sub module option as shown in Figure 5.18. First, the person in charge needs to define the component name and then input all attributes of the component in order to define a component. The attributes of the component are the shape, the material, the diameter, the length, the width, the height, the thickness, the weight, and the procurement strategy. For a cylinder-like shape of component, the material, the diameter, the length, the weight, and the procurement strategy are required. For a box-like shape of component, the material, the length, the width, the thickness, the weight, and the procurement strategy are required.

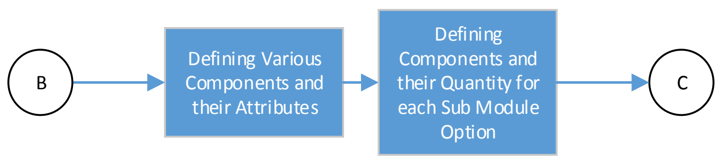

Figure 5.18. Storing data into Master Database to Generate Component

Then, the person in charge needs to define the relationship between component and the sub module. Each sub module option consists of one or more components depending on its component type. The part type of the sub module option consists of one component. The sub assembly type of the sub module option consists of more than one component. To define the relationship, the person in charge requires selecting a sub module option and a component and then entering the quantity of the component for each sub module option.

For an in-house component, several additional attributes are required to be defined as shown in Figure 5.19. The required attributes of an in-house component are its basic shapes, shape complexities, and shape complexity types. For that reason, various basic shapes and shape complexities need to be defined. Meanwhile, various shape complexity types are already defined in the system and the person in charge is not required to define them. In addition, two more attributes also need to be defined before defining the in-house component and its attributes, which are the required material property and the required surface finish.

In order to define an in-house component, its basic shape, shape complexity, and shape complexity type must be selected for each in-house component. Then, the person in charge could enter the required size tolerance, the required surface roughness, and the required material property, if they are required. To define the required surface finish, the person in charge is required to define the surface finish name and then to determine whether the surface finish name will be used as a basic surface finishing process or not. If the surface finish name is used as a basic surface finishing process, then the surface finish name will be used as the additional process before conducting other surface finishing processes. Finally, the person in charge needs to enter the manufacturing complexity coefficient for the in-house component.

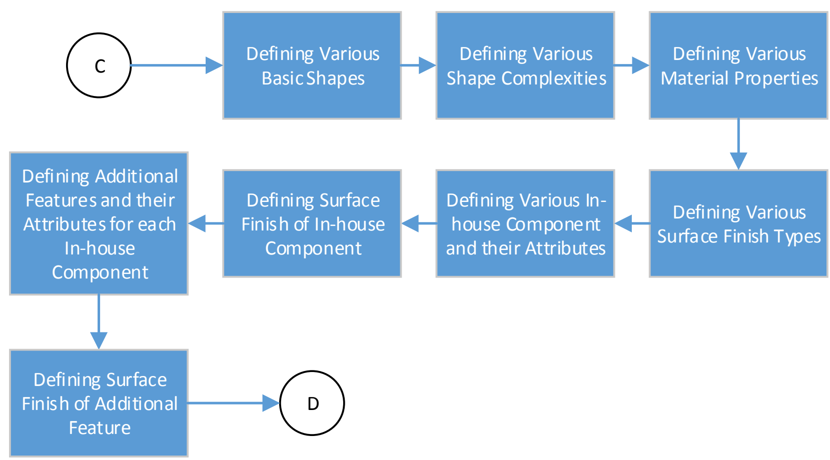

Figure 5.19. Storing data into Master Database to Generate In-house Component and Its Attributes

An in-house component could have an additional feature. To define an additional feature, the person in charge is required to define the name of the additional feature and select the type of the additional feature for the in-house component. Various additional features types are already defined in the system. Therefore, the person in charge is not required to define them. Each additional feature of an in-house component has its own attributes. For that reason, the person in charge is required to enter the quantity, the diameter, the length, the width, and thickness of each additional feature. For a cylinder-like shape of an additional feature, the person in charge needs to enter the quantity, the diameter, and the length. For a box-like shape of an additional feature, the person in charge needs to enter the quantity, the length, the width, and the thickness. In addition, the required size tolerance, the required surface roughness, and the required surface finish of each additional feature could be inputted if they are required.

5.3.2 Storing Data into Master Database for Activities and Resources Generation

The purpose of the second part of the system is to generate the activities and resources consumed by the product family that is developed. The consumed activity and resource are dependent on the required processes. Therefore, the person in charge is required to define various processes that exist in the market and their type categorisation. To define a process, the person in charge is required to write the process name down and then select the type of process. The process types are already defined in the system and the person in charge is not required to define them. Then, the person in charge needs to build the database to generate assembly method, joining process, and the disassembly process, the database to generate manufacturing process, the database to generate outsourcing process for component and material, and the database to generate the activity and resource.

Figure 5.20 shows the steps to define the process and build the database in order to generate the assembly method and joining process. After defining various processes, the person in charge needs to define various factors with the value that will determine the viable assembly methods and the viable joining processes to assemble the components of the product family. First, it is required to define various factors in determining the viable assembly method that can be used to pick, orient, insert, and place a component before it is joined with another component. The viable assembly method relies on the type of assembly environment, number of product variants of all product families, and the production volume of all product variants. Various assembly methods are already defined in the system. The assembly environment type is also already defined in the system so the person in charge is not required to define it again. Therefore, the person in charge only needs to define the relationship between the factors and their values with the assembly method. In this step, the person in charge is required to define an assembly method for a combination of assembly environment, number of product variants of all product families, and production volume of all product variants.

Next, the person in charge needs to define the relationship between the joining process and all factors with their values that influence the joining process. The viable joining process relies on the component material, the component thickness, the joining production volume, and the type of degree of permanence. The degree of permanence type is already defined in the system so the person in charge is not required to define them again. In defining the relationship between a joining process and its factors, the person in charge defines a joining process with its assembly/disassembly complexity coefficient and then its component material, material thickness, degree of permanence, and production volume. As many different materials are also needing to be joined, the person in charge is required to define the joining process for the components with different materials. In this case, the person in charge is required to define a joining process with its assembly/disassembly complexity coefficient for a combination of material thickness, degree of permanence, and production volume.

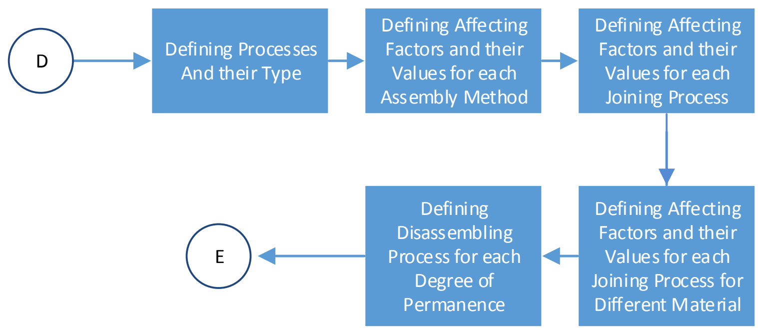

Figure 5.20. Storing Data into Master Database to Generate Assembly Method and Joining Process

To recover the taken back product, it is required to define the viable disassembling processes to disassemble the taken back product into its sub module or component. In this step, the person in charge needs to define various disassembling processes that can be used for each degree of permanence.

The next stage is to build the database to generate the manufacturing process. Figure 5.21 shows the steps to build the database in order to generate the manufacturing process. Only a certain number of manufacturing processes are viable to manufacture a material in a certain range of production volume. For that reason, the person in charge is required to define the viable manufacturing processes for a combination of materials and production volume. This step is used to develop the manufacturing process database for a combination of materials and production volumes.

The viable tertiary manufacturing process is dependent on the shape, the shape complexity, and the shape complexity type of the component. The shape, the shape complexity, and the shape complexity type of the component are already explained in

Section 4.7.1. For that reason, the next step is to define the viable tertiary manufacturing processes for a combination of basic shape, shape complexity, and shape complexity type. In this step, first, the person in charge is required to define the manufacturing process. Then, the person in charge must define the basic shape, the shape complexity, and the shape complexity type for each manufacturing process. The selection of the viable primary and secondary manufacturing processes to manufacture a certain basic shape and shape complexity requires a raw material shape as an input. Therefore, first, the raw material shape needs to be defined. After that, the person in charge needs to define the viable manufacturing processes for a combination of basic shape, shape complexity, shape complexity type, and the raw material shape.

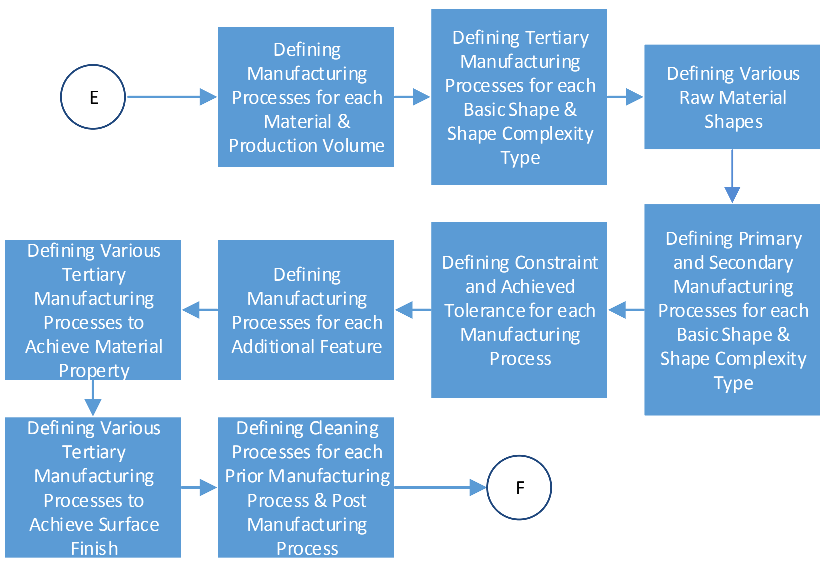

Figure 5.21. Storing Data into Master Database to Generate Manufacturing Process

Each manufacturing process has its own constraints in manufacturing a component such as a minimum and maximum diameter and weight. In addition, each manufacturing process can achieve a different range of size tolerance and surface roughness. The constraint and the achieved tolerance of the manufacturing process depend on the material of the component. For that reason, the person in charge is required to define the minimum and maximum diameter, length, thickness, and weight that can be manufactured, by using a combination of process type, process name, and material. In addition, the person in charge is required to define the minimum and maximum size tolerance and surface roughness that can be achieved by using a combination of process type, process name, and material.

As an in-house component could have an additional feature, the viable manufacturing processes for the additional feature are also required to be defined. In this step, the person in charge is required to define the manufacturing process for each type of additional feature.

The next step is to define the viable tertiary manufacturing processes to achieve a certain required material property and the viable tertiary manufacturing processes to achieve a surface finish. First, the person in charge is required to define the tertiary manufacturing process for a combination of material and material properties. Then, the person in charge is required to define the viable tertiary manufacturing process for a combination of material and surface finishes to define the process to achieve the required surface finish.

After the person in charge defines various viable manufacturing processes, the next step is to define various viable cleaning processes. In this step, the person in charge needs to define the viable cleaning processes for a combination of prior and post processes. The post process is the selected tertiary manufacturing process to achieve the required surface finish. The prior process is the process before the selected tertiary manufacturing process to achieve the required surface finish. The person in charge could select more than one tertiary manufacturing process to achieve the required surface finish for either the main shape or the additional feature. As a result, the combination of the prior and post processes and also the cleaning process could be more than one for either the main shape or the additional feature.

Figure 5.22 presents the steps to build the database in order to generate the outsourcing process. First, the person in charge is required to define various regions of the supplier and various suppliers of outsourced component and material. Then the outsourcing process of the outsourced component database is developed. This database consists of information about the outsourced component name, the supplier name of the component, the minimum order of the component, the batch order of the component, and the price of the component. After that, the outsourcing process of the material database is developed. This database consists of information about the material name, the shape of the material, the supplier name of the material, the minimum order of the material, the batch order of the material, and the price of the material.

In the last stage, the person in charge is required to define various departments and their resources, various activities and their activity drivers, various activities conducted at each department, various categories of activity, and the time required for each activity. The steps to build the database in order to generate the required activity and resource are shown in Figure 5.23. To define the department, the person in charge needs to define the name of the department, the quantity and the rate of the labour and supervisor, the quantity and the rate of equipment, the quantity and the rate of the supplies, the quantity and the rate of utilities, and the quantity of and the rate facilities.

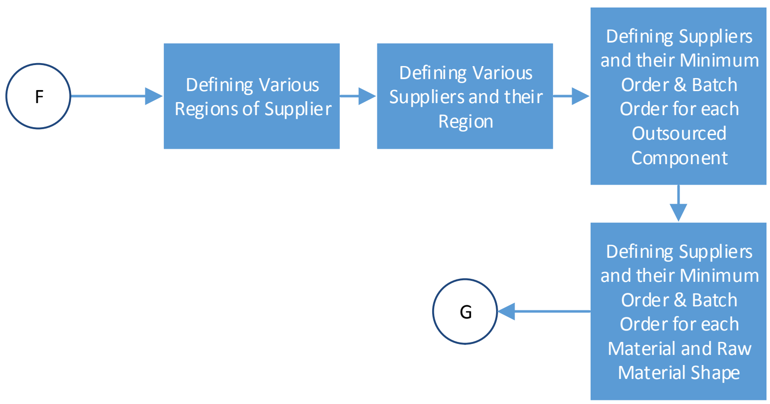

Figure 5.22. Storing Data into Master Database to Generate Outsourcing Process

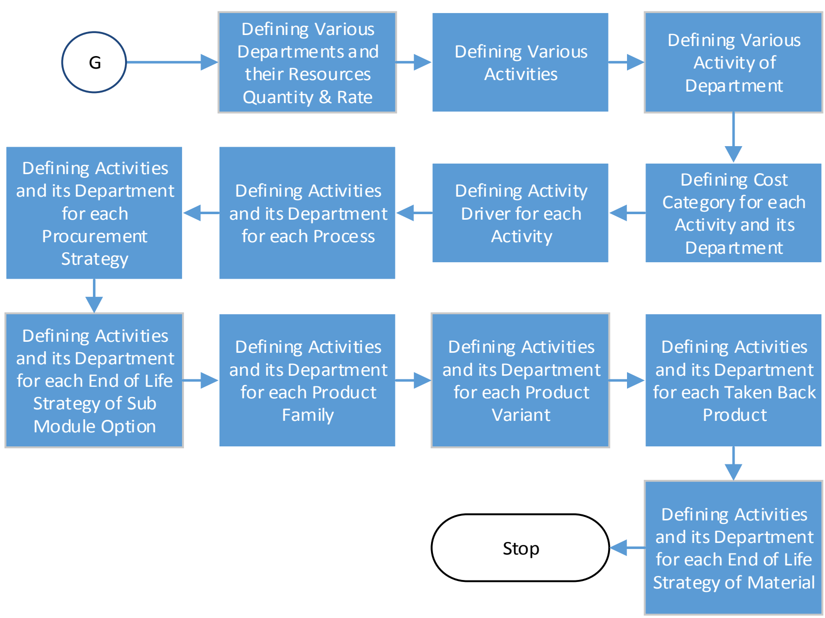

Figure 5.23. Storing Data into Master Database to Generate Activity and Resource

After that, the person in charge needs to define various activities that are conducted in order to produce a product family. Each component, sub module option, product platform, assembly sequence of product platform, product variant, and assembly sequence of product variant has its own factors that influence the conducted activity. For that reason, the person in charge also needs to define the activity driver for each component, sub module option, product platform, assembly sequence of product platform, product variant, and assembly sequence of product variant. First, the person in charge selects a component, a sub module option, a product platform, an assembly sequence of product platform, a product variant, or an assembly sequence and then the person in charge selects its activity driver.

The conducted activities in each department are not the same. The person in charge needs to define all the activities of each department. First, the person in charge needs to select a department, and then select all activities conducted in the department. In addition, the conducted activity and the related department will be different for different processes, different end of life strategies, different procurement strategies, and different product levels. For that reason, the person in charge needs to define the activity, the department, and the required activity time for each process, end of life strategy, procurement strategy, and product level. First, the person in charge needs to select a combination of department and activity for each process, end of life strategy, procurement strategy, or product level, and then define the required time for performing the activity at the department.

Each activity can be categorised into the component level and the life cycle stage of a product family. Therefore, the person in charge needs to define the category of each activity. First, the person in charge selects an activity and its department, then the person in charge select the category of the activity. This categorisation will be used to group the cost of the activity into each component level cost and each life cycle cost.

5.4 STORING DATA INTO TRANSACTION DATABASE

After all required master databases are completed, the user can start to implement the system prototype by storing the required data into the transaction databases. The transaction databases are used to store the required inputs in order to estimate the life cycle cost of a product family. First, the user needs to store the required inputs into the transaction databases to generate the components and their attributes of the product family that is developed. Then the required inputs to generate all activities and resources consumed by the product family must be stored into the transaction databases. The calculation the life cycle cost of each component level of the product family does not require any input from the user. Therefore, no input from the user is required for the last part of the system.

5.4.1 Storing Data into Transaction Database for Components and Attributes Generation

Figure 5.24 and Figure 5.26 present the steps that must be followed by the user to store the required data into the transaction database of the first part of the system. These steps are used to generate the components of the product family that is developed and their attributes.

The steps to store the required data into the transaction database in order to generate various modules of each product variant are shown in Figure 5.24. The first step in generating the components and their attributes is to input all product families whose cost needs to be estimated. The user is required to write the name of the product family to create the product family. After all product families have been inputted, the user is required to input all product variants of each product family, their production volume, and the percentage of the product variant that can be taken back at its end of life. The user is required to write the product variant name, select the product family to which the product variant belongs and input the production volume of the product variant. Then, the user needs to input the percentage of the taken back product of the production volume for the product variant. Figure 5.25 shows the example of the user interface to add, modify, delete, and find the developed product family data in the transaction database.

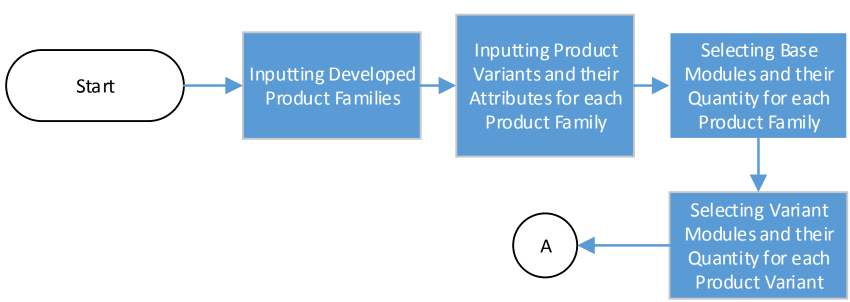

Figure 5.24. Storing data into Transaction Database to Generate Module of each Product Variant

The next step is to select all base modules for each product family and to determine the quantity of each base module. The base module is a module that is required by all product variants of the same product family. The base module is selected by inputting the sub function required by the customers, the preferred concept to carry out the sub function, the utilisation of all product variants of the same product family, and the specific factors or the description of the module. First, the user needs to select the product family. Then, the user selects the sub function, the concept, the utilisation, and the specific factors. If the required module is not found, then the user must define the module in the master database. After the user selects the base module, the user needs to determine the quantity of the base module for each product family.

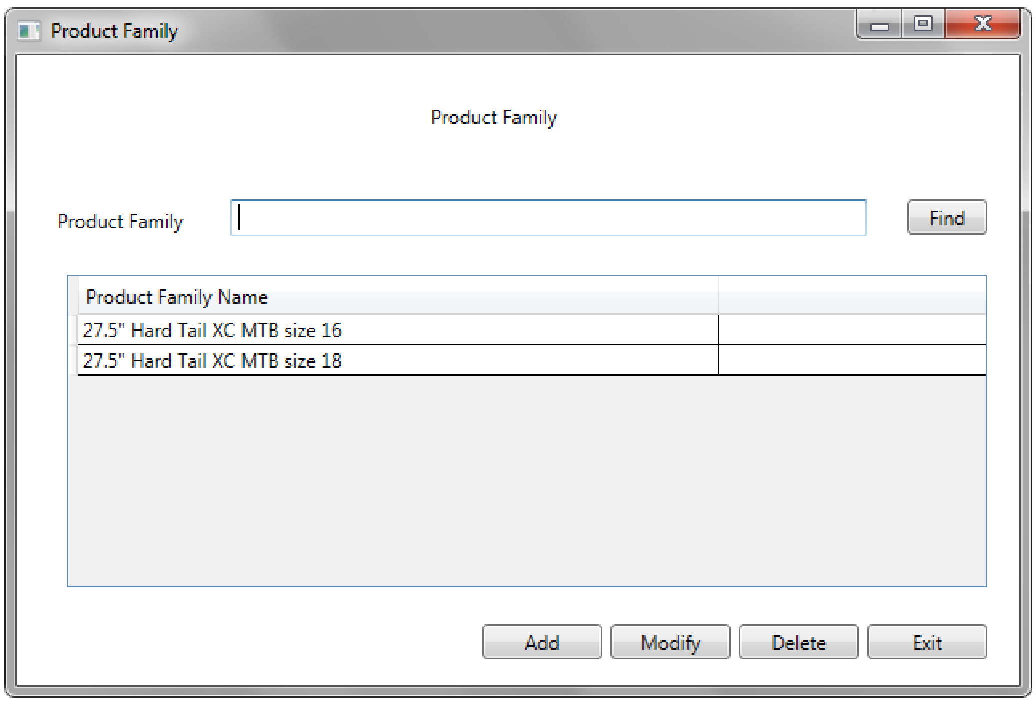

Figure 5.25. User Interface to Store Product Family data into Transaction Database

Then, the user need to select all variant modules for each product variant and determine the quantity of each variant module. The variant module is a module that is required by each product variant. Similar to the base module, the variant module is also selected by inputting the sub function required by the customers, the preferred concept to carry out the sub function, the utilisation of each product variant, and the specific factors or the description of the module. After selecting the variant module, the quantity of the variant module for each product variant needs to be determined.

Each base module consists of one or more sub modules. For each sub module, various sub module options are available in the market. For that reason, the next step in implementing the prototype is to select the sub module option for each sub module of the base module as shown in Figure 5.26. First, the user needs to select the product family. Then, the system will generate all sub modules for the product family. The sub module of the product family is generated based on the base module of the product family. After that, the user needs to select the sub module whose sub module option is going to be determined. Then, the system will generate all sub module options that are available for the selected sub module. Finally, the user needs to select one sub module option that is going to be used to carry out the required sub function.

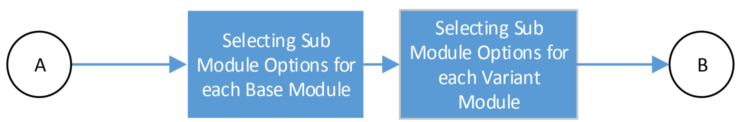

Figure 5.26. Storing data into Transaction Database to Generate Sub Module Option of each Module

Similar to the base module, each variant module consists of one or more sub modules. Therefore, the next step in implementing the prototype is to select the sub module option for each sub module of the variant module. The procedure to select the sub module option for the variant module is similar to the base module. First, the user needs to select the product variant. Then, the user needs to select the sub module that is going to be defined. Finally, the user needs to select one sub module option that is going to be used to carry out the required sub function.

5.4.2 Storing Data into Transaction Database for Activities and Resources Generation

The steps that must be followed by the user to implement the second part of the system are shown in Figure 5.27, Figure 5.28, and Figure 5.29. These steps are used to generate all activities and resources consumed by the product family that is developed. The expected output of the second part of the system is all activities and resources consumed by the product family. As the consumed activity and resource depend on the required process, the user needs to select the process required by the product family. Prior to selecting the required process, the user needs to input all required information determining the viable process to the transaction database of the system.

Figure 5.27 presents the steps to generate assembly method and joining process. To be able to select the assembly method and the joining process for the product platform, first, the user needs to select the product family, input the assembly sequence number, select the first assembled component, select the second assembled component, input the repetition of the assembly sequence, select the degree of permanence of the assembly sequence, select the assembly environment of the assembly sequence, and input the coefficient of the assembly complexity. Then, the system will generate the suitable assembly method and various viable joining processes for each sequence. Based on the generated information, the user must select one of the viable joining processes as the selected process that will be implemented for each sequence.

Next, the user needs to select the assembly method and the joining process for the product variant. Similar to the product platform, the user needs to select the product variant, input the assembly sequence number, select the first assembled component, select the second assembled component, input the repetition of the assembly sequence, select the degree of permanence of the assembly sequence, select the assembly environment of the assembly sequence, and input the coefficient of the assembly complexity. After the system generates the suitable assembly method and various viable joining processes for each sequence, the user needs to select one joining process that will be implemented for each sequence.

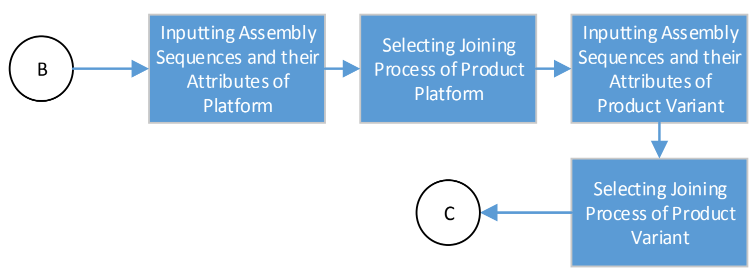

Figure 5.27. Storing data into Transaction Database to Generate Assembly Method and Joining Process

After that, the steps to generate the manufacturing process are shown in Figure 5.28. The user needs to select the primary or secondary manufacturing process to manufacture the main shape of the in-house component. First, the user needs to select the in-house component whose process is going to be selected. Then, the system will generate the viable combinations of raw material shape and manufacturing process to manufacture the in-house component. The system will also generate the size tolerance and surface roughness achieved by each viable manufacturing process. Finally, the user needs to select one of the combinations by clicking the selected process.

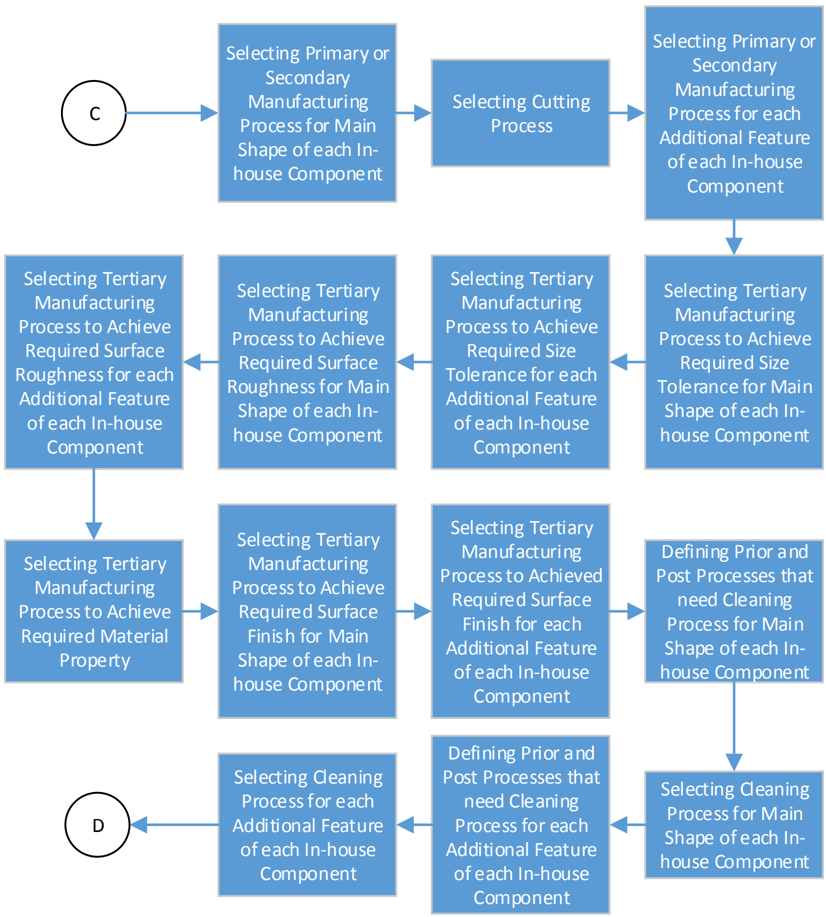

Figure 5.28. Storing data into Transaction Database to Generate Manufacturing Process

If the selected process to manufacture the main shape of the in-house component is the secondary manufacturing process, the user needs to select the cutting process to cut the raw material. To generate the viable cutting processes, the user needs to select the in-house component whose process is going to be selected. Then, the system will generate all viable cutting processes to cut the raw material. The procedure to select the cutting process is similar to the primary or secondary manufacturing process.

After selecting the primary and secondary manufacturing processes for the main shape, the user needs to select the primary and secondary manufacturing processes for the additional feature of the in-house component. The system will generate all viable manufacturing processes to manufacture the additional feature of the in-house component. The system will also generate the size tolerance and surface roughness achieved by each viable manufacturing process. The procedure to select the primary or secondary manufacturing process for the additional feature is similar to the main shape.

Next, if the required size tolerance is not achieved, the user needs to select the tertiary manufacturing process to achieve the required size tolerance for the main shape of the in-house component. The user also needs to select the tertiary manufacturing process to achieve the required size tolerance for the additional feature of the in-house component. The system will generate all viable tertiary manufacturing processes to achieve the required size tolerance. The system will also generate the surface roughness achieved by each viable manufacturing process. The procedure to select the tertiary manufacturing process for the main shape and for the additional feature is similar to the primary or secondary manufacturing process.

If the required surface roughness for the main shape of the in-house component is not achieved, first, the user needs to select the in-house component. Then, the system will generate all viable tertiary manufacturing processes and the surface roughness achieved by each tertiary manufacturing process. Finally, the user needs to select one of the viable tertiary manufacturing processes by clicking the selected process. Similar steps need to be conducted to select the tertiary manufacturing process to achieve the surface roughness for the additional feature. The procedure to select the tertiary manufacturing process to achieve the surface roughness for the additional feature of the in-house component is similar to the main shape.

Then, if it is required, the user needs to select the tertiary manufacturing process to achieve the required material property of the in-house component. To select the tertiary manufacturing process to achieve the required material property, first, the user needs to select the in-house component. Then, the system will generate the required material property of the in-house component and all viable tertiary manufacturing processes to achieve the required material property. Finally, the user needs to select one of the viable tertiary manufacturing processes by clicking the selected process.

If the tertiary manufacturing process to achieve the required surface finish for the main shape of the in-house component is required, first, the user needs to select the in-house component. Then, the system will generate the required surface finish of the in-house component and all viable tertiary manufacturing processes that can be used to achieve the required surface finish. Finally, the user needs to select the tertiary manufacturing process that will be used to achieve the required surface finish by clicking the selected process. Similar steps are required to select the tertiary process to achieve the required surface finish for the additional feature of the in-house component. The procedure to select the tertiary process to achieve the required surface finish for the additional feature is similar to the main shape.

Next, if it is required, the user needs to select the cleaning process of the main shape of the in-house component. First, the user needs to select the in-house component name, the prior process, and the post process. Then, the system will generate all viable cleaning processes. After that, the user needs to select the cleaning process that will be implemented for the main shape. To select the cleaning process for the additional feature of the in-house component, first, the user needs to select the in-house component, the additional feature type, and the additional feature name. Then, the user needs to select the prior process and the post process for the additional feature. The system will generate all viable cleaning processes for the additional feature. Finally, the user needs to select the cleaning process that will be implemented for the additional feature.

In addition, the user also needs to store data to generate the outsourcing process of each outsourced component and material. The steps to generate the outsourcing process are shown in Figure 5.29. First, the user needs to select the outsourced component name. Then the system will generate the quantity of the outsourced component that needs to be bought. The system also will generate all suppliers that sell the outsourced component with their region, minimum order, batch order, and the price of the outsourced component. Finally, the user needs to click the supplier that is selected to supply the outsourced component. Similar steps are also required to input the supplier for the material. First, the user needs to select the material name and the raw material name. Then, the system will generate the quantity of the material that need to be purchased, all suppliers that sell the material with their region, minimum order, batch order, and the price of the material. The procedure to select the supplier for the material is similar to the outsourced component. After that, the system will generate the all activities and resources consumed by the product family.

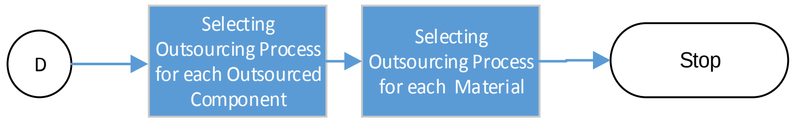

Figure 5.29. Storing data into Transaction Database to Generate Outsourcing Process

5.5 EVALUATING THE SYSTEM PROTOTYPE

After the master and transaction databases have been completed by storing the required data, the evaluation process of the system prototype can be started. The first purpose of the system prototype evaluation is to evaluate the functionality of the system prototype that has been built. The functionality of the system prototype is evaluated by testing each menu of the system prototype whether it can provide the specified function or not. The functionality evaluation has been conducted simultaneously with the data storage process by adding, modifying, and deleting data in the master database and transaction database categories of each step described in Section 5.3 and Section 5.4.

The second purpose of the system evaluation is to verify the result of the system prototype. This evaluation is performed by comparing the result of the system prototype against the manual process. This evaluation has been conducted by inputting several examples for each step and verifying the result. To verify the result of the system prototype, the generated reports of each step are evaluated by comparing the generated data against the data from the manual process.

Chapter 6: Time-driven Life Cycle Cost Estimation System Evaluation

This chapter describes how the developed time-driven life cycle cost estimation system is evaluated. The first section of this chapter explains how the application evaluation is conducted to evaluate the developed system. Then, Section 6.2 explains the success evaluation process conducted in this research to evaluate the developed system. Finally, the summary of the evaluation process is outlined in the last section.

6.1 APPLICATION EVALUATION

To assess the applicability against the aim and objectives of the developed time-driven life cycle cost estimation system, the application evaluation is performed by conducting a case study to estimate the life cycle cost of two different product families. The case study is used to find out whether the developed system is able to

1. allocate and then calculate the life cycle cost to each component level of a product family
2. be easily adapted for different technologies and approaches
3. determine the end of life strategy for each sub module of a product family
4. integrate the end of life strategy into the life cycle cost model in order to estimate the life cycle cost of a product family
5. take into account different structures of different product families and estimate their life cycle cost with less time and effort
6. transform the market segment, the production volume, the product family structure, and the product family function into the required activities and resources information.

In the case study, the developed system is implemented to estimate the life cycle cost of 27.5” hard tail cross country sport mountain bicycle families. The 27.5” hard tail cross country sport mountain bicycle families consists of two bicycle families, which are 27.5” hard tail cross country sport mountain bicycle size 16 and size 18. Each bicycle family consists of Cozmix CX1.0 27.5 and Cozmix CX2.0 27.5 bicycle variants as shown in Figure 6.1 and Figure 6.2.

As explained in the previous chapter, the master and transaction databases must be built and completed before the case study is conducted. The steps to store the required data into the master database have been already described in Section 5.3. However, the data storage process of the master databases for the case study is not presented further in this section because it is only a tedious manual process of inputting data. This section only presents the implementation of the system to estimate the life cycle cost of the bicycle. All required data for the database has been collected from the archival record of the collaborating company and from literature.

Figure 6.1. Cozmix CX1.0 27.5 (Cozmix CX1.0 27.5, 2015)

Figure 6.2. Cozmix CX2.0 27.5 (Cozmix CX2.0 27.5, 2015)

6.1.1 Case Study: Generating Component and its Attributes

The first stage in estimating the life cycle cost of the 27.5” hard tail cross country sport mountain bicycle families is generating the components and their attributes of the product family. In order to generate the components and their attributes of the product family, first, the bicycle families and their product variants data are inputted. The production volume and the percentage of the taken back of each product variant are also required to be inputted. The 27.5” hard tail cross country sport bicycle families, the product variants of each product family, the production volume of each product variant, and the percentage of taken back of each product variant are shown in Table 6.1. Figure 6.3 shows the user interface to define the product family that is developed. The user interface to input the product variant and its attributes is shown in Figure 6.4.

Table 6.1. Product Variant and Attributes of 27.5” Hard Tail Cross Country Sport MTB Family

Product Family	Product Variant	Production Volume	%Taken Back Product
27.5“ Hard Tail XC MTB size 16	Cozmix CX1.0 27.5 size 16	40,000	50
	Cozmix CX2.0 27.5 size 16	20,000	50
27.5“ Hard Tail XC MTB size 18	Cozmix CX1.0 27.5 size 18	40,000	50
	Cozmix CX2.0 27.5 size 18	20,000	50

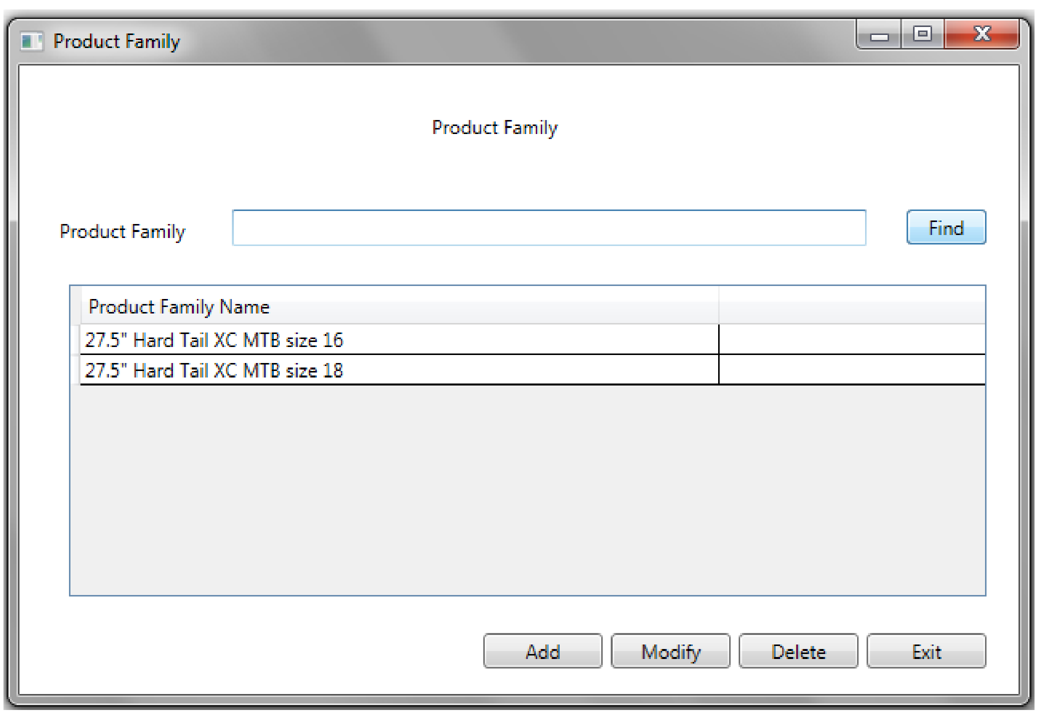

Figure 6.3. User Interface to Define Product Family

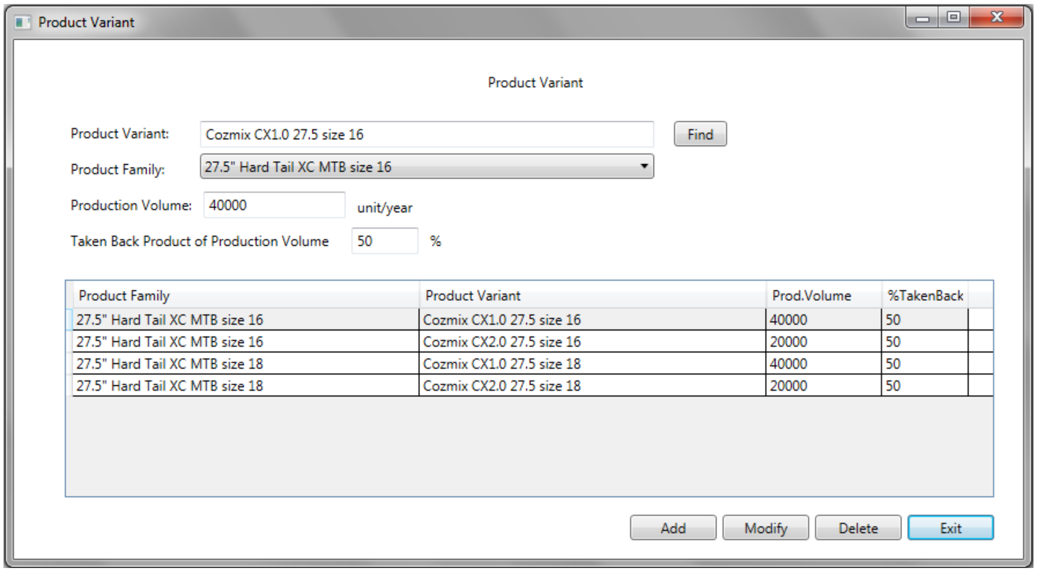

Figure 6.4. User Interface to Input Product Variant

The proposed system will use the input to calculate the quantity of the production runs and the quantity of the product orders required for each product variant. The product variants that are developed with their attributes are shown in Appendix A1.

Then, all base modules for each product family and the quantity of each base module are determined. The user interface to input the base module of each product family is shown in Figure 6.5. The base module is determined by inputting the required sub functions of all product variants in each product family, the preferred concept to carry out the sub function, the utilisation of all product variants, and the specific factors or the description of the selected based module listed in Table 6.2. These inputs are identified and collected from various literatures and then conformed by the collaborating company. Based on the inputs, the developed system generates the base modules for each product family as shown in Appendix A2. After the base modules are generated, the quantity of each base module must also be inputted.

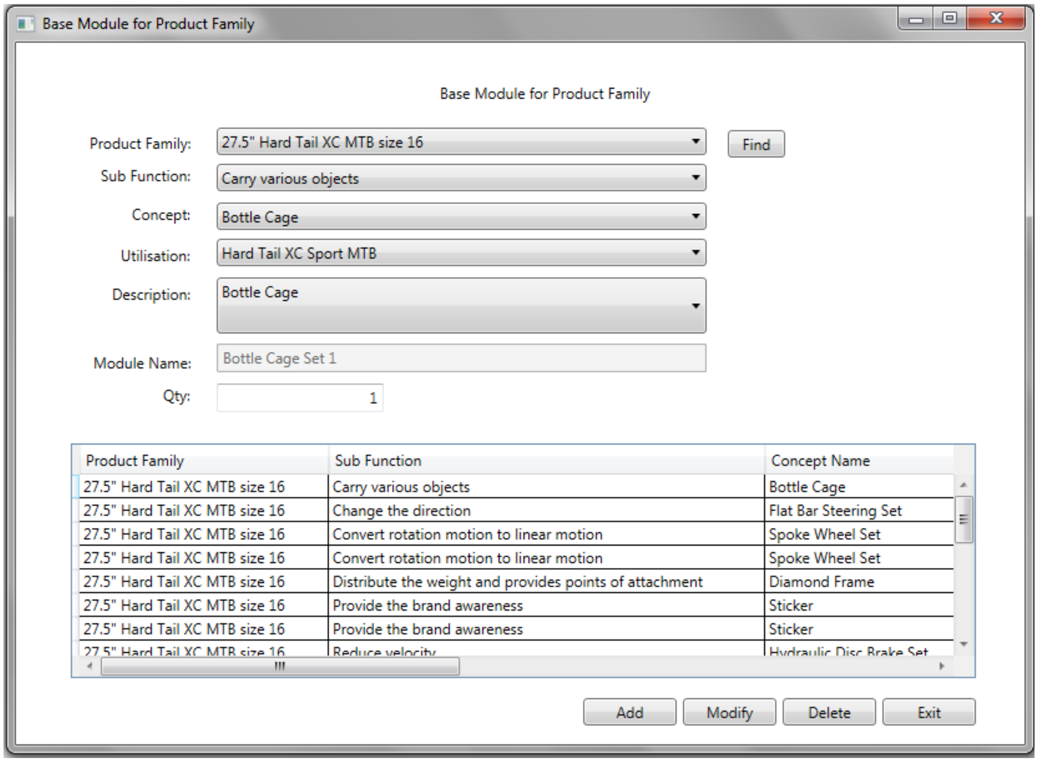

Figure 6.5. User Interface to Input Base Module of a Product Family

Table 6.2. Inputs to Determine the Base Module of 27.5” Hard Tail Cross Country Sport MTB Family

Product Family	Sub Function	Concept	Utilisation	Specific Factor	Quantity
27.5“ Hard Tail XC MTB size 16	Distribute the rider weight and provides points of attachment for various components	Diamond Frame	Hard Tail XC Sport MTB	Diamond, No Hinge	1
	Reduce velocity	Hydraulic Disc Brake Set	Hard Tail XC Sport MTB	Hydraulic Disc Brake , Flat Lever, Single Cable, No Detangler	1
	Convert rotation motion to linear motion	Spoke Wheel Set	Hard Tail XC Sport MTB	27.5", Front Axle Skewer, Front Hub, Double Wall Clincher Rim, Tube Tyre	1
	Convert rotation motion to linear motion	Spoke Wheel Set	Hard Tail XC Sport MTB	27.5", Rear Axle Skewer, Rear Free Hub, Double Wall Clincher Rim, Tube Tyre	1
	Support the rider	Racing Saddle Set	Hard Tail XC Sport MTB	Rigid Post, Bracket Saddle Clamp, Quick Release Frame Clamp	1
	Change the direction	Flat Bar Steering Set	Hard Tail XC Sport MTB	Flat Bar, Semi Integrated Head Set, Threadless Stem, Coil Spring Suspension Fork	1
	Provide the brand awareness	Sticker	Hard Tail XC Sport MTB	Sticker SNI	1

Product Family	Sub Function	Concept	Utilisation	Specific Factor	Quantity
	Provide the brand awareness	Sticker	Hard Tail XC Sport MTB	Sticker Company	1
	Stand the bicycle frame	Side Kick Stand	Hard Tail XC Sport MTB	Side Kick Stand	1
	Carry various objects	Bottle Cage	Hard Tail XC Sport MTB	Bottle Cage	1
27.5“ Hard Tail XC MTB size 18	Distribute the rider weight and provides points of attachment for various components	Diamond Frame	Hard Tail XC Sport MTB	Diamond, No Hinge	1
	Reduce velocity	Hydraulic Disc Brake Set	Hard Tail XC Sport MTB	Hydraulic Disc Brake , Flat Lever, Single Cable, No Detangler	1
	Convert rotation motion to linear motion	Spoke Wheel Set	Hard Tail XC Sport MTB	27.5", Front Axle Skewer, Front Hub, Double Wall Clincher Rim, Tube Tyre	1
	Convert rotation motion to linear motion	Spoke Wheel Set	Hard Tail XC Sport MTB	27.5", Rear Axle Skewer, Rear Free Hub, Double Wall Clincher Rim, Tube Tyre	1
	Support the rider	Racing Saddle Set	Hard Tail XC Sport MTB	Rigid Post, Bracket Saddle Clamp, Quick Release Frame Clamp	1
	Change the direction	Flat Bar Steering Set	Hard Tail XC Sport MTB	Flat Bar, Semi Integrated Head Set, Threadless Stem, Coil Spring Suspension Fork	1
	Provide the brand awareness	Sticker	Hard Tail XC Sport MTB	Sticker SNI	1
	Provide the brand awareness	Sticker	Hard Tail XC Sport MTB	Sticker Company	1
	Stand the bicycle frame	Side Kick Stand	Hard Tail XC Sport MTB	Side Kick Stand	1
	Carry various objects	Bottle Cage	Hard Tail XC Sport MTB	Bottle Cage	1

After the base module has been determined, the variant modules of each product variant with their quantity are determined. The user interface to input the product variant and its attributes is shown in Figure 6.6. Similar to the base module, the variant module is determined by inputting the required sub functions of each product variant, the preferred concept to carry out the sub function, the utilisation of all product variants, and the specific factors of the selected variant module listed in Table 6.3. The generated variant modules for each product variant are shown in Appendix A3. After the variant modules are generated, the quantity of each variant module must also be inputted.

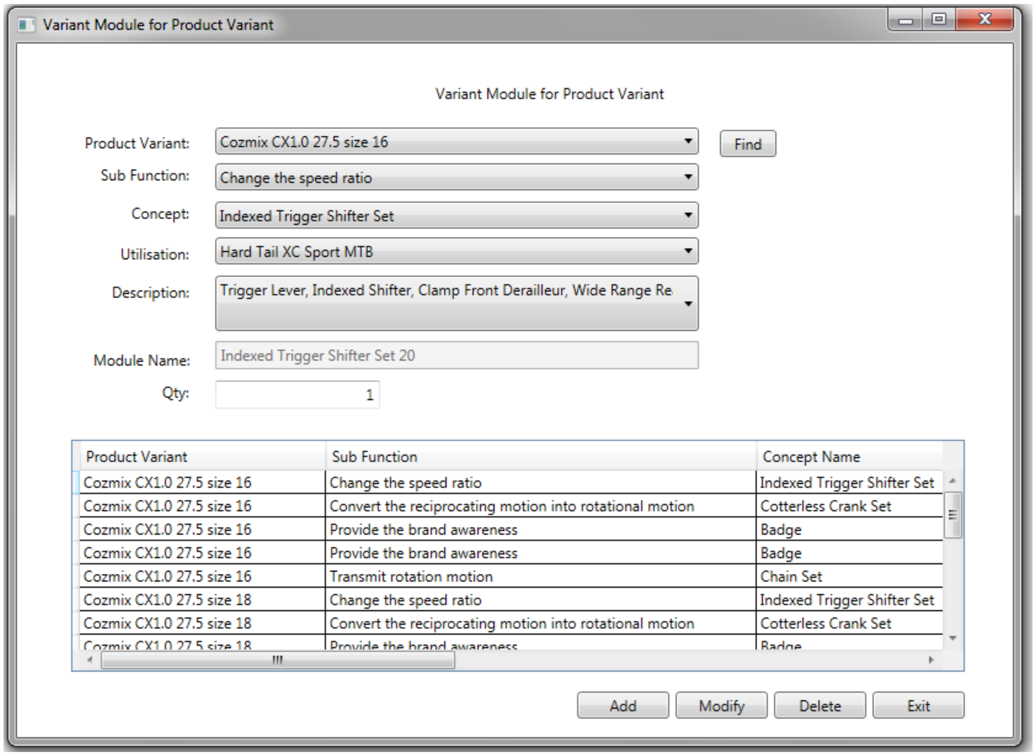

Figure 6.6. User Interface to Input Variant Module of a Product Variant

Table 6.3. Inputs to Determine the Variant Module of 27.5” Hard Tail Cross Country Sport MTB Variant

Product Variant	Sub Function	Concept	Utilisation	Specific Factor	Quantity
Cozmix CX1.0 27.5 size 16	Change the speed ratio	Indexed Trigger Shifter Set	Hard Tail XC Sport MTB	Trigger Lever, Indexed Shifter, Clamp Front Derailleur, Wide Range Rear Derailleur	1
	Convert the reciprocating motion into rotational motion	Cotterless Crank Set	Hard Tail XC Sport MTB	Quill Pedal, 2 pieces Cotterless, Cartridge Bottom Bracket, Triple Chain Wheel Front Sprocket	1
	Transmit rotation motion	Chain Set	Hard Tail XC Sport MTB	Standard Chain, Cassette Rear Sprocket	1
	Provide the brand awareness	Badge	Hard Tail XC Sport MTB	Steering Badge	1
	Provide the brand awareness	Badge	Hard Tail XC Sport MTB	Frame Badge	1
Cozmix CX2.0 27.5 size 16	Change the speed ratio	Indexed Trigger Shifter Set	Hard Tail XC Sport MTB	Trigger Lever, Indexed Shifter, Clamp Front Derailleur, Wide Range Rear Derailleur	1
	Convert the reciprocating motion into rotational motion	Cotterless Crank Set	Hard Tail XC Sport MTB	Quill Pedal, 2 pieces Cotterless, External Bottom Bracket, Triple Chain Wheel Front Sprocket	1
	Transmit	Chain Set	Hard Tail XC	Standard Chain, Cassette	1

Product Variant	Sub Function	Concept	Utilisation	Specific Factor	Quantity
	rotation motion		Sport MTB	Rear Sprocket	
	Provide the brand awareness	Badge	Hard Tail XC Sport MTB	Steering Badge	1
	Provide the brand awareness	Badge	Hard Tail XC Sport MTB	Frame Badge	1
Cozmix CX1.0 27.5 size 18	Change the speed ratio	Indexed Trigger Shifter Set	Hard Tail XC Sport MTB	Trigger Lever, Indexed Shifter, Clamp Front Derailleur, Wide Range Rear Derailleur	1
	Convert the reciprocating motion into rotational motion	Cotterless Crank Set	Hard Tail XC Sport MTB	Quill Pedal, 2 pieces Cotterless, Cartridge Bottom Bracket, Triple Chain Wheel Front Sprocket	1
	Transmit rotation motion	Chain Set	Hard Tail XC Sport MTB	Standard Chain, Cassette Rear Sprocket	1
	Provide the brand awareness	Badge	Hard Tail XC Sport MTB	Steering Badge	1
	Provide the brand awareness	Badge	Hard Tail XC Sport MTB	Frame Badge	1
Cozmix CX2.0 27.5 size 18	Change the speed ratio	Indexed Trigger Shifter Set	Hard Tail XC Sport MTB	Trigger Lever, Indexed Shifter, Clamp Front Derailleur, Wide Range Rear Derailleur	1
	Convert the reciprocating motion into rotational motion	Cotterless Crank Set	Hard Tail XC Sport MTB	Quill Pedal, 2 pieces Cotterless, External Bottom Bracket, Triple Chain Wheel Front Sprocket	1
	Transmit rotation motion	Chain Set	Hard Tail XC Sport MTB	Standard Chain, Cassette Rear Sprocket	1
	Provide the brand awareness	Badge	Hard Tail XC Sport MTB	Steering Badge	1
	Provide the brand awareness	Badge	Hard Tail XC Sport MTB	Frame Badge	1

Next, various sub module options with their quantity for each sub module of the base module are generated by the developed system. The user interface to select the sub module option for the base module is shown in Figure 6.7. The user needs to select one of the generated sub module options that will be used. The selected sub module option of each base module and its quantity is shown in Appendix A4. The user interface to select the sub module option for the variant module is similar to the base module as shown in Figure 6.8. The sub module option with its quantity for each sub module of the variant module is also selected in a similar way to the base module. The selected sub module option of each variant module and its quantity is shown in Appendix A5.

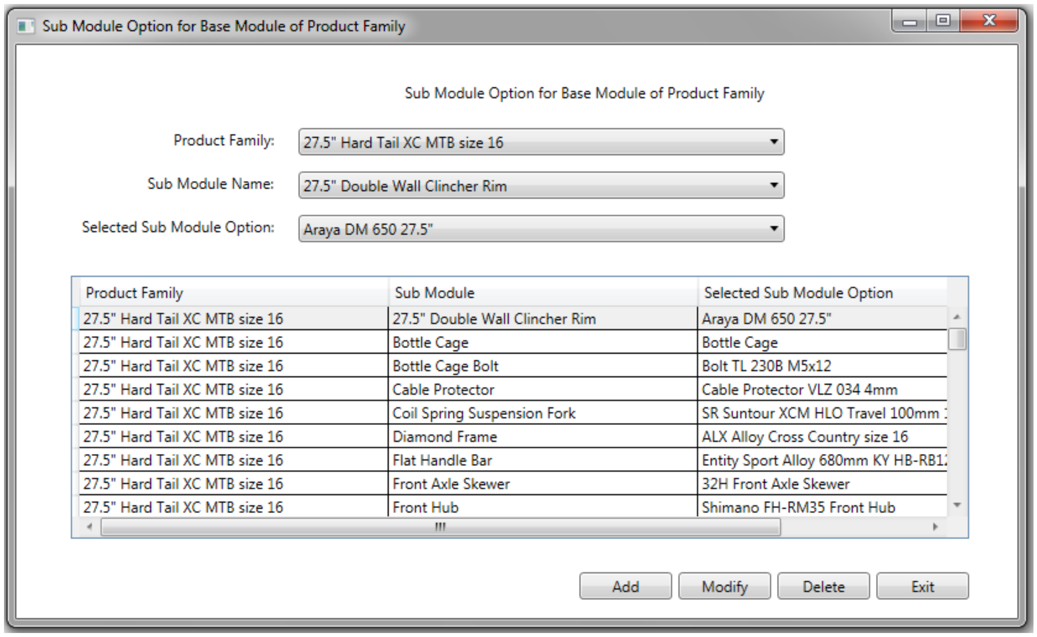

Figure 6.7. User Interface to Select the Sub Module Option for Base Module

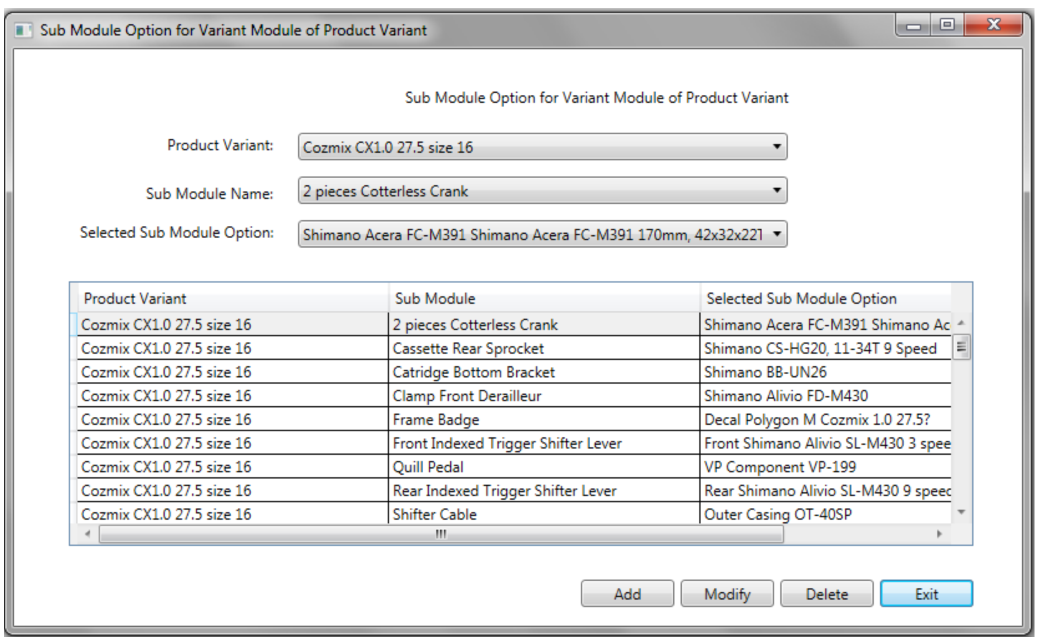

Figure 6.8. User Interface to Select the Sub Module Option for Variant Module

Finally, each sub module option is divided by the developed system into its components with their quantity for each sub module option, diameter, length, width, height, thickness, material, weight, and procurement strategy. The components of each product variant with their quantity and procurement strategy are shown in Appendix A6. For the in-house component, the system also generates its basic shape, shape complexity, shape complexity type, required size tolerance, required surface roughness, required material property, required surface finish, and additional feature. The attributes of each in-house component are shown in Appendix A7. Appendix A8 shows the attributes of each additional feature of the in-house component.

6.1.2 Case Study: Generating Activity and Resource

The second stage in estimating the life cycle cost of the 27.5” hard tail cross country sport mountain bicycle families is generating all activities and resources consumed by the product family. First, the component assembly sequences and their attributes of the platform of the 27.5” hard tail cross country sport mountain bicycle are inputted. The user interface to input the component assembly sequences and their attributes is shown in Figure 6.9. The assembly sequences and their attributes for each product platform of the 27.5” hard tail cross country sport mountain bicycle families are shown in Table 6.4. Based on the inputs, the developed system generates the assembly method and the viable joining processes for each component assembly sequence. Then, the user needs to select the process that will be implemented as shown in Figure 6.10. The assembly method and the selected joining process for each component assembly sequence are shown in Appendix A9.

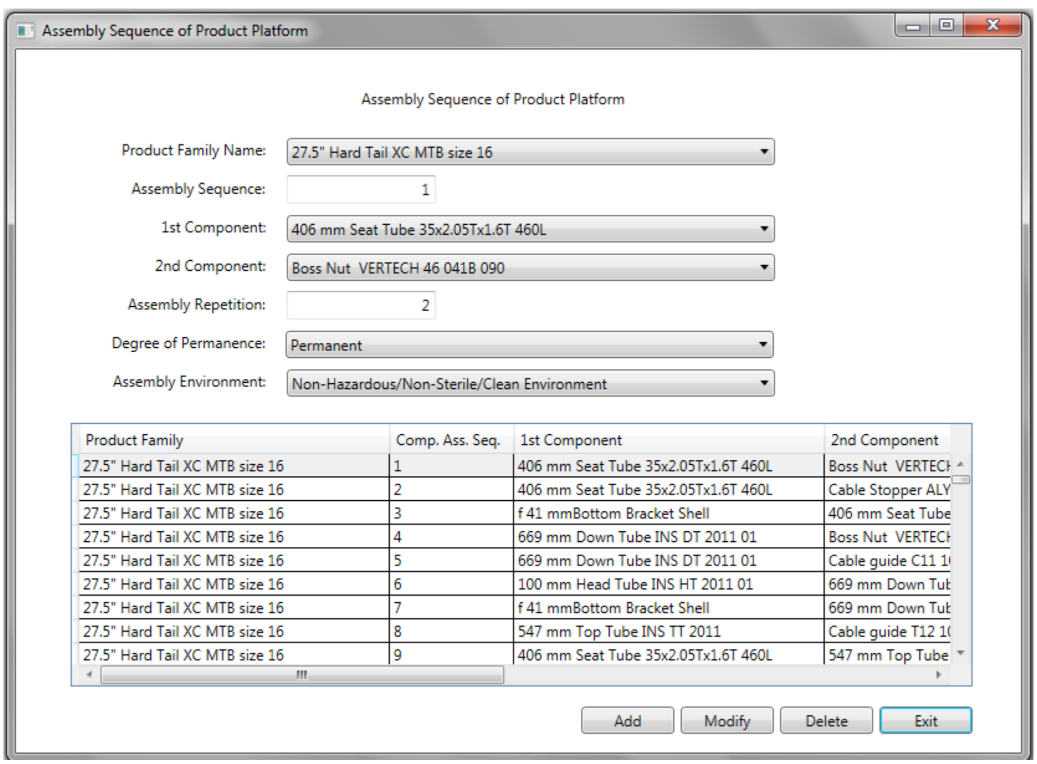

Figure 6.9. User Interface to Input the Component Assembly Sequence of Product Platform

Table 6.4. Component Assembly Sequence for Product Platform of 27.5" Hard Tail Cross Country Sport MTB Family

Product Family	Assembled Components		Assembly Repetition	Degree of Permanence	Assembly Environment
	1st Component	2nd Component			
27.5" Hard Tail XC MTB size 16	406 mm Seat Tube 35x2.05Tx1.6T 460L	Boss Nut VERTECH 46 041B 090	2	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	406 mm Seat Tube 35x2.05Tx1.6T 460L	Cable Stopper ALY JS AL3 1P	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	ϕ 41 mm Bottom Bracket Shell	406 mm Seat Tube 35x2.05Tx1.6T 460L	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	669 mm Down Tube INS DT 2011 01	Boss Nut VERTECH 46 041B 090	2	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	669 mm Down Tube INS DT 2011 01	Cable guide C11 101 095 Alloy	3	Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	669 mm Down Tube INS DT 2011 01	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	ϕ 41 mm Bottom Bracket Shell	669 mm Down Tube INS DT 2011 01	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	547 mm Top Tube INS TT 2011	Cable guide T12 101 175 2in1	3	Permanent	Non-Hazardous or Non-Sterile/Clean
	406 mm Seat Tube 35x2.05Tx1.6T 460L	547 mm Top Tube INS TT 2011	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	547 mm Top Tube INS TT 2011	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	425 mm Chain Stay INS CS 2011	Cable guide C11 101 095 Alloy	2	Permanent	Non-Hazardous or Non-Sterile/Clean
	425 mm Chain Stay INS CS 2011	End Frame INS RE 2012 001 Right	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	425 mm Chain Stay INS CS 2011	End Frame INS RE 2012 001 Left	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	ϕ 41 mm Bottom Bracket Shell	425 mm Chain Stay INS CS 2011	2	Permanent	Non-Hazardous or Non-Sterile/Clean
	424 mm Seat Stay INS SS 2011	Cable guide C11 101 095 Alloy	2	Permanent	Non-Hazardous or Non-Sterile/Clean
	406 mm Seat Tube 35x2.05Tx1.6T 460L	424 mm Seat Stay INS SS 2011	2	Permanent	Non-Hazardous or Non-Sterile/Clean
	424 mm Seat	Seat Stay Bracket	1	Permanent	Non-Hazardous

Product	Assembled Components		Assembly	Degree of	Assembly
	Stay INS SS 2011	INS BR 2011			or Non-Sterile/Clean
	425 mm Chain Stay INS CS 2011	424 mm Seat Stay INS SS 2011	2	Permanent	Non-Hazardous or Non-Sterile/Clean
	406 mm Seat Tube 35x2.05Tx1.6T 460L	Promax 342Q 34.2QR	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	406 mm Seat Tube 35x2.05Tx1.6T 460L	Sticker SNI Poly M Cozmic CX 27.5	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	406 mm Seat Tube 35x2.05Tx1.6T 460L	Sticker Insera Sena 5x4 cm	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	669 mm Down Tube INS DT 2011 01	Decal Polygon M Cozmix 1.0 27.5”	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	Bearing 1SI110	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x5 mm	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x10 mm	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Bearing 1SI110	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x5 mm	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x10 mm	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	Stem Cap SP 23 BK ϕ28.6	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Handle Grip VLG1312AD2L Lock	2	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Front Brake Lever Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15	Rear Brake Lever Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean

Product	Assembled Components		Assembly	Degree of	Assembly
	ϕ31.8 Clamp Stem NDC				
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Entity Expert Alloy 90mm CHUN-E IRS-06 ϕ28.6	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano FH-RM35 BL	Spoke 14G x 270	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Eyelet 14G x 270	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Eyelet 14G x 270	Spoke 14G x 270	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Eyelet 14G x 270	Nipple 14G x 270	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Rim Tape Nylon Red 650B x 20mm	1	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Schwalbe SV 19	1	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Schwalbe Smart Sam 27.5”x2.10”	1	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano FH-RM35 BL	Shimano SM-RT30 160 mm	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	32H ϕ9 mm l=108 mm Skewer	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	32H ϕ9 mm l=108 mm Skewer	32H Front Spring	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	32H ϕ9 mm l=108 mm Skewer	32H ϕ9 mm Nut	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Bracket Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Bracket Shimano Acera BR-M395	Caliper Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Caliper Shimano Acera BR-M395	Hose Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Front Brake Lever Shimano Acera BR-M395	Hose Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Saddle Steel Rail Velo Flux B XC	Saddle	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean

Product	Assembled Components		Assembly	Degree of	Assembly
	Entity Xpert Alloy 30.9x350mm Kalloy SP712N	Saddle Steel Rail Velo Flux B XC	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	ϕ 41 mm Bottom Bracket Shell	Bracket 37-015B-290 M6	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Bracket 37-015B-290 M6	Side Kick Stand	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Bottle Cage	Bottle Bolt TL 230B M5x12	2	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Boss Nut VERTECH 46 041B 090	Bottle Bolt TL 230B M5x12	2	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano FH-RM35 BZBL	Spoke 14G x 272	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Eyelet 14G x 272	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Eyelet 14G x 272	Spoke 14G x 272	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Eyelet 14G x 272	Nipple 14G x 272	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Rim Tape Nylon Red 650B x 20mm	1	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Schwalbe SV 19	1	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Schwalbe Smart Sam 27.5”x2.10”	1	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano FH-RM35 BZBL	Shimano SM-RT30 160 mm	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	424 mm Seat Stay INS SS 2011	Bracket Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Bracket Shimano Acera BR-M395	Caliper Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Caliper Shimano Acera BR-M395	Hose Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Rear Brake Lever Shimano Acera BR-M395	Hose Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
27.5“ Hard Tail XC MTB size 18	457 mm Seat Tube 35x2.05Tx1.6T 460L	Boss Nut VERTECH 46 041B 090	2	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	457 mm Seat	Cable Stopper	1	Permanent	Non-Hazardous

Product	Assembled Components		Assembly	Degree of	Assembly
	Tube 35x2.05Tx1.6T 460L	ALY JS AL3 1P			or Non-Sterile/Clean
	ϕ 41 mm Bottom Bracket Shell	457 mm Seat Tube 35x2.05Tx1.6T 460L	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	690 mm Down Tube INS DT 2011 01	Boss Nut VERTECH 46 041B 090	2	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	690 mm Down Tube INS DT 2011 01	Cable guide C11 101 095 Alloy	3	Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	690 mm Down Tube INS DT 2011 01	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	ϕ 41 mm Bottom Bracket Shell	690 mm Down Tube INS DT 2011 01	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	561 mm Top Tube INS TT 2011	Cable guide T12 101 175 2in1	3	Permanent	Non-Hazardous or Non-Sterile/Clean
	457 mm Seat Tube 35x2.05Tx1.6T 460L	561 mm Top Tube INS TT 2011	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	561 mm Top Tube INS TT 2011	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	425 mm Chain Stay INS CS 2011	Cable guide C11 101 095 Alloy	2	Permanent	Non-Hazardous or Non-Sterile/Clean
	425 mm Chain Stay INS CS 2011	End Frame INS RE 2012 001 Right	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	425 mm Chain Stay INS CS 2011	End Frame INS RE 2012 001 Left	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	ϕ 41 mm Bottom Bracket Shell	425 mm Chain Stay INS CS 2011	2	Permanent	Non-Hazardous or Non-Sterile/Clean
	512 mm Seat Stay INS SS 2011	Cable guide C11 101 095 Alloy	2	Permanent	Non-Hazardous or Non-Sterile/Clean
	457 mm Seat Tube 35x2.05Tx1.6T 460L	512 mm Seat Stay INS SS 2011	2	Permanent	Non-Hazardous or Non-Sterile/Clean
	512 mm Seat Stay INS SS 2011	Seat Stay Bracket INS BR 2011	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	425 mm Chain Stay INS CS 2011	512 mm Seat Stay INS SS 2011	2	Permanent	Non-Hazardous or Non-Sterile/Clean
	457 mm Seat Tube 35x2.05Tx1.6T 460L	Promax 342Q 34.2QR	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean

Product	Assembled Components		Assembly	Degree of	Assembly
	457 mm Seat Tube 35x2.05Tx1.6T 460L	Sticker SNI Poly M Cozmic CX 27.5	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	457 mm Seat Tube 35x2.05Tx1.6T 460L	Sticker Insera Sena 5x4 cm	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	690 mm Down Tube INS DT 2011 01	Decal Polygon M Cozmix 1.0 27.5”	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	Bearing 1SI110	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x5 mm	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x10 mm	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Bearing 1SI110	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x5 mm	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x10 mm	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	100 mm Head Tube INS HT 2011 01	Stem Cap SP 23 BK ϕ28.6	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Handle Grip VLG1312AD2L Lock	2	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Front Brake Lever Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Rear Brake Lever Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Entity Expert Alloy 90mm CHUN-E IRS-06 ϕ28.6	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano FH-	Spoke 14G x 270	32	Non-	Non-Hazardous

Product	Assembled Components		Assembly	Degree of	Assembly
	RM35 BL			Permanent	or Non-Sterile/Clean
	Araya DM 650 27.5"	Eyelet 14G x 270	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Eyelet 14G x 270	Spoke 14G x 270	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Eyelet 14G x 270	Nipple 14G x 270	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Rim Tape Nylon Red 650B x 20mm	1	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Schwalbe SV 19	1	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Schwalbe Smart Sam 27.5”x2.10”	1	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano FH-RM35 BL	Shimano SM-RT30 160 mm	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	32H ϕ9 mm l=108 mm Skewer	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	32H ϕ9 mm l=108 mm Skewer	32H Front Spring	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	32H ϕ9 mm l=108 mm Skewer	32H ϕ9 mm Nut	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Bracket Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Bracket Shimano Acera BR-M395	Caliper Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Caliper Shimano Acera BR-M395	Hose Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Front Brake Lever Shimano Acera BR-M395	Hose Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Saddle Steel Rail Velo Flux B XC	Saddle	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 30.9x350mm Kalloy SP712N	Saddle Steel Rail Velo Flux B XC	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	ϕ 41 mm Bottom Bracket Shell	Bracket 37-015B-290 M6	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Bracket 37-015B-290 M6	Side Kick Stand	1	Non-Permanent	Non-Hazardous or Non-

Product	Assembled Components		Assembly	Degree of	Assembly
					Sterile/Clean
	Bottle Cage	Bottle Bolt TL 230B M5x12	2	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Boss Nut VERTECH 46 041B 090	Bottle Bolt TL 230B M5x12	2	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano FH-RM35 BZBL	Spoke 14G x 272	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Eyelet 14G x 272	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Eyelet 14G x 272	Spoke 14G x 272	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Eyelet 14G x 272	Nipple 14G x 272	32	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Rim Tape Nylon Red 650B x 20mm	1	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Schwalbe SV 19	1	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	Schwalbe Smart Sam 27.5”x2.10”	1	Semi-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano FH-RM35 BZBL	Shimano SM-RT30 160 mm	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	512 mm Seat Stay INS SS 2011	Bracket Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Bracket Shimano Acera BR-M395	Caliper Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Caliper Shimano Acera BR-M395	Hose Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Rear Brake Lever Shimano Acera BR-M395	Hose Shimano Acera BR-M395	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean

After that, the component assembly sequences and their attributes of the variant of the 27.5” hard tail cross country sport mountain bicycle are also inputted. The user interface to input the component assembly sequences and the attributes of the variant are similar to the product platform as shown in Figure 6.11. Table 6.5 shows the assembly sequences and their attributes for each variant of the 27.5” hard tail cross country sport mountain bicycle variants. Based on the inputs, the developed system generates the assembly method and the viable joining process for each component assembly sequence for the variant of 27.5” hard tail cross country sport mountain bicycle. Then, the user needs to select the process that will be implemented as shown in Figure 6.12.The assembly method and the joining process for each component assembly sequence are shown in Appendix A10.

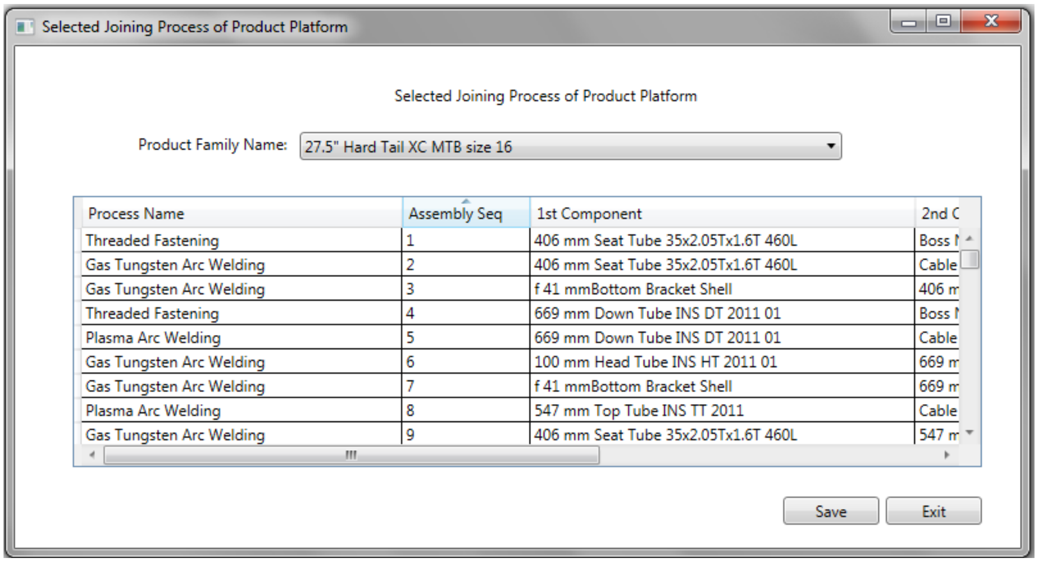

Figure 6.10. User Interface to Select the Joining Process of Product Platform

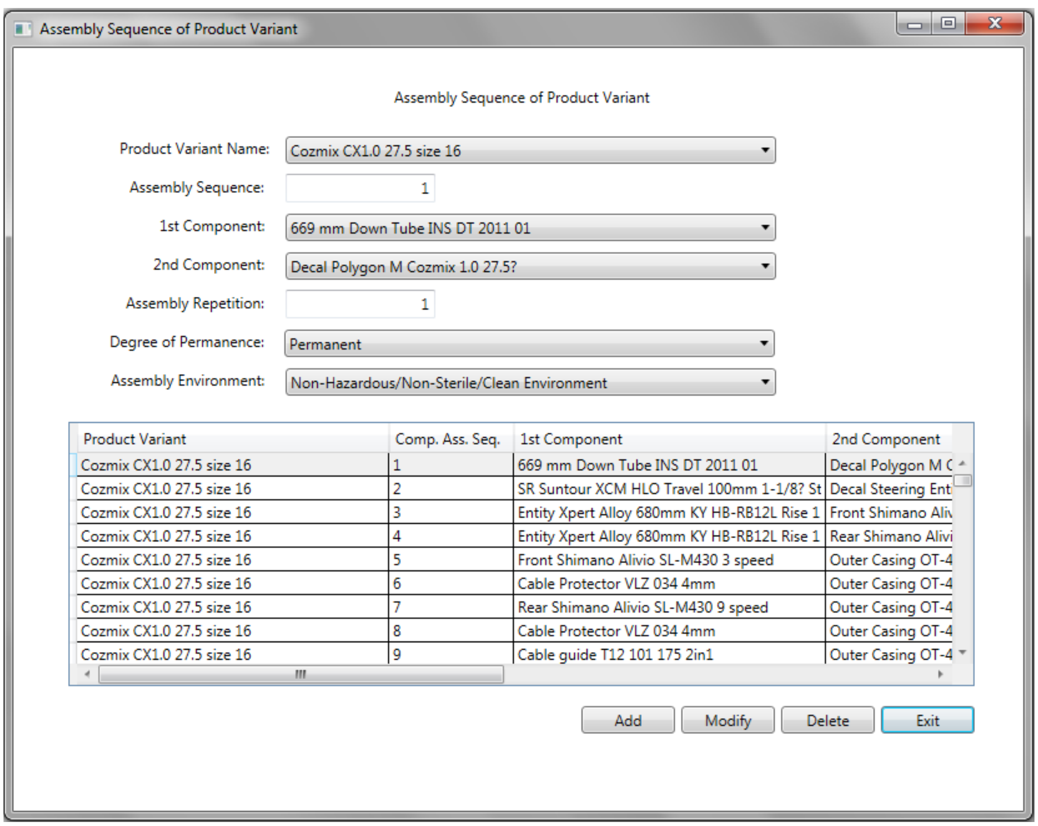

Figure 6.11. User Interface to Input the Component Assembly Sequence for Variant

Table 6.5. Component Assembly Sequence for Variant of 27.5" Hard Tail Cross Country Sport MTB Variant

Product Variant	Assembled Components		Assembly Repetition	Degree of Permanence	Assembly Environment
	1st Component	2nd Component			
Cozmix CX1.0 27.5 size 16	669 mm Down Tube INS DT 2011 01	Decal Polygon M Cozmix 1.0 27.5"	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	SR Suntour XCM HLO Travel 100mm 1-1/8" Steerer	Decal Steering Entity Xpert	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Front Shimano Alivio SL-M430 3 speed	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Rear Shimano Alivio SL-M430 9 speed	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Front Shimano Alivio SL-M430 3 speed	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Rear Shimano Alivio SL-M430 9 speed	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cable guide T12 101 175 2in1	Outer Casing OT-40SP	2	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	ϕ 41 mm Bottom Bracket Shell	Cartridge Shimano BB-UN26	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cartridge Shimano BB-UN26	Lockring Shimano BB-UN26	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cartridge Shimano BB-UN26	Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	Left Arm Shimano Acera FC-M391 170mm, 42x32x22T	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Left Arm Shimano Acera	Crank Cup Shimano Acera FC-	1	Non-Permanent	Non-Hazardous or Non-

Product	Assembled Components		Assembly	Degree of	Assembly
	FC-M391 170mm, 42x32x22T	M391 170mm, 42x32x22T			Sterile/Clean
	406 mm Seat Tube 35x2.05Tx1.6T 460L	Shimano Alivio FD-M430	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano Alivio FD-M430	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	End Frame INS RE 2012 001 Right	Shimano Deore RD-M592SGS	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano Deore RD-M592SGS	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	32H ϕ10 mm l=145 mm Skewer	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	End Frame INS RE 2012 001 Right	32H ϕ10 mm l=145 mm Skewer	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	32H ϕ10 mm l=145 mm Skewer	32H Rear Spring	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	32H ϕ10 mm l=145 mm Skewer	32H ϕ10 mm Nut	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	KMC X-9 PGY 1/2x11/128x110 Links Super Light	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano FH-RM35 BZBL	Shimano CS-HG20, 11-34T 9 Speed	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano CS-HG20, 11-34T 9 Speed	KMC X-9 PGY 1/2x11/128x110 Links Super Light	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
Cozmix CX2.0 27.5 size 16	669 mm Down Tube INS DT 2011 01	Decal Polygon M Cozmix 2.0 27.5”	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Decal Steering Entity Xpert	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Front Shimano Deore SL-M610 3 speed	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp	Rear Shimano Deore SL-M610 10 speed	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean

Product	Assembled Components		Assembly	Degree of	Assembly
	Stem NDC				
	Front Shimano Deore SL-M610 3 speed	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Rear Shimano Deore SL-M610 10 speed	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cable guide T12 101 175 2in1	Outer Casing OT-40SP	2	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	ϕ 41 mm Bottom Bracket Shell	Right Cup and Bearing Shimano Hollowtech 2	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Right Cup and Bearing Shimano Hollowtech 2	Left Cup Shimano Hollowtech 2	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Right Cup and Bearing Shimano Hollowtech 2	Right Arm with Spindle Shimano Deore FC-M610	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Right Arm with Spindle Shimano Deore FC-M610	Left Arm Shimano Deore FC-M610	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Left Arm Shimano Deore FC-M610	Crank Cup Shimano Deore FC-M610	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	406 mm Seat Tube 35x2.05Tx1.6T 460L	Shimano Deore FD-M610	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano Deore FD-M610	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	End Frame INS RE 2012 001 Right	Shimano Deore RD-M610SGS	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano Deore RD-M610SGS	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	32H ϕ10 mm l=145 mm Skewer	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	End Frame INS RE 2012 001 Right	32H ϕ10 mm l=145 mm Skewer	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	32H ϕ10 mm l=145 mm Skewer	32H Rear Spring	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	32H ϕ10 mm l=145 mm	32H ϕ10 mm Nut	1	Non-Permanent	Non-Hazardous or Non-

Product	Assembled Components		Assembly	Degree of	Assembly
	Skewer				Sterile/Clean
	Right Arm with Spindle Shimano Deore FC-M610	Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116 links	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano FH-RM35 BZBL	Shimano Deore CS-HG62, 11-36T, 10 Speed	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano Deore CS-HG62, 11-36T, 10 Speed	Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116 links	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
Cozmix CX1.0 27.5 size 18	690 mm Down Tube INS DT 2011 01	Decal Polygon M Cozmix 1.0 27.5”	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Decal Steering Entity Xpert	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Front Shimano Alivio SL-M430 3 speed	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Rear Shimano Alivio SL-M430 9 speed	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Front Shimano Alivio SL-M430 3 speed	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Rear Shimano Alivio SL-M430 9 speed	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cable guide T12 101 175 2in1	Outer Casing OT-40SP	2	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	ϕ 41 mm Bottom Bracket Shell	Cartridge Shimano BB-UN26	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cartridge Shimano BB-UN26	Lockring Shimano BB-UN26	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cartridge Shimano BB-UN26	Right Arm with Spindle Shimano Acera FC-M391 170mm,	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean

Product	Assembled Components		Assembly	Degree of	Assembly
		42x32x22T			
	Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	Left Arm Shimano Acera FC-M391 170mm, 42x32x22T	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Left Arm Shimano Acera FC-M391 170mm, 42x32x22T	Crank Cup Shimano Acera FC-M391 170mm, 42x32x22T	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	457 mm Seat Tube 35x2.05Tx1.6T 460L	Shimano Alivio FD-M430	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano Alivio FD-M430	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	End Frame INS RE 2012 001 Right	Shimano Deore RD-M592SGS	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano Deore RD-M592SGS	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	32H ϕ10 mm l=145 mm Skewer	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	End Frame INS RE 2012 001 Right	32H ϕ10 mm l=145 mm Skewer	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	32H ϕ10 mm l=145 mm Skewer	32H Rear Spring	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	32H ϕ10 mm l=145 mm Skewer	32H ϕ10 mm Nut	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	KMC X-9 PGY 1/2x11/128x110 Links Super Light	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano FH-RM35 BZBL	Shimano CS-HG20, 11-34T 9 Speed	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano CS-HG20, 11-34T 9 Speed	KMC X-9 PGY 1/2x11/128x110 Links Super Light	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
Cozmix CX2.0 27.5 size 18	690 mm Down Tube INS DT 2011 01	Decal Polygon M Cozmix 2.0 27.5”	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Decal Steering Entity Xpert	1	Permanent	Non-Hazardous or Non-Sterile/Clean
	Entity Xpert Alloy 680mm	Front Shimano Deore SL-M610 3	1	Non-Permanent	Non-Hazardous or Non-

Product	Assembled Components		Assembly	Degree of	Assembly
	KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	speed			Sterile/Clean
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Rear Shimano Deore SL-M610 10 speed	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Front Shimano Deore SL-M610 3 speed	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Rear Shimano Deore SL-M610 10 speed	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Cable guide T12 101 175 2in1	Outer Casing OT-40SP	2	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	ϕ 41 mm Bottom Bracket Shell	Right Cup and Bearing Shimano Hollowtech 2	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Right Cup and Bearing Shimano Hollowtech 2	Left Cup Shimano Hollowtech 2	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Right Cup and Bearing Shimano Hollowtech 2	Right Arm with Spindle Shimano Deore FC-M610	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Right Arm with Spindle Shimano Deore FC-M610	Left Arm Shimano Deore FC-M610	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Left Arm Shimano Deore FC-M610	Crank Cup Shimano Deore FC-M610	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	457 mm Seat Tube 35x2.05Tx1.6T 460L	Shimano Deore FD-M610	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano Deore FD-M610	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	End Frame INS RE 2012 001 Right	Shimano Deore RD-M610SGS	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano Deore RD-M610SGS	Outer Casing OT-40SP	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Araya DM 650 27.5"	32H ϕ10 mm l=145 mm Skewer	1	Non-Permanent	Non-Hazardous or Non-

Product	Assembled Components		Assembly	Degree of	Assembly
					Sterile/Clean
	End Frame INS RE 2012 001 Right	32H ϕ10 mm l=145 mm Skewer	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	32H ϕ10 mm l=145 mm Skewer	32H Rear Spring	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	32H ϕ10 mm l=145 mm Skewer	32H ϕ10 mm Nut	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Right Arm with Spindle Shimano Deore FC-M610	Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116 links	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano FH-RM35 BZBL	Shimano Deore CS-HG62, 11-36T, 10 Speed	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean
	Shimano Deore CS-HG62, 11-36T, 10 Speed	Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116 links	1	Non-Permanent	Non-Hazardous or Non-Sterile/Clean

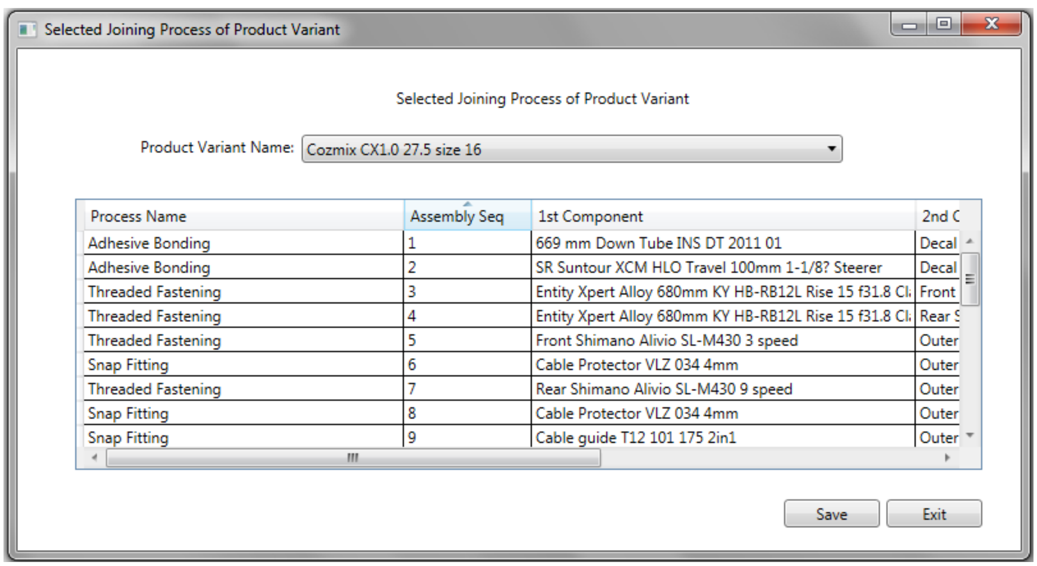

Figure 6.12. User Interface to Select the Joining Process of Product Platform

In the next step, the percentage of taken back product of the production volume for each product variant of the 27.5” hard tail cross country sport mountain bicycle families is used to generate the quantity of each recovered sub module. The percentage of taken back product of the production volume for each product variant is already presented in Table 6.1. The component type and the quantity of each recovered sub module are shown in Appendix A11. As a sub assembly type of recovered sub module consists of more than one component, it is divided to its recovered components. The total quantity of each recovered component is shown in Appendix A12.

The sub module that cannot be recovered is used as a recovered material. The shape of the recovered material mostly is bulk material. If the sub assembly type of sub module cannot be recovered, then it is divided into its unrecovered components. The quantity of the each unrecovered component with its material, quantity, and end of life strategy are shown in Appendix A13. The total weight of each recovered material is shown in Appendix A14.

Next, based on the attributes of the in-house component, the developed system generates all viable primary and secondary processes that can be implemented to manufacture the main shape of the in-house component. Appendix A15 shows the viable primary and secondary processes for each in-house component of 27.5” hard tail cross country sport mountain bicycle families. Then, the user must select one of the viable processes to manufacture the main shape of an in-house component. Appendix A16 shows the selected manufacturing process and its achieved size tolerance and surface roughness.

As the selected manufacturing process is one of the secondary manufacturing processes, the developed system also generates all viable cutting processes for the selected manufacturing process that is categorised as a secondary manufacturing process. The user must select one of the cutting processes to cut the raw material used for the in-house component. The viable and the selected cutting process are shown in Appendix A17.

Four of the in-house components of the 27.5” hard tail cross country sport mountain bicycle families have an additional feature. Therefore the developed system generates all viable primary or secondary manufacturing processes to manufacture the additional feature. The viable and selected manufacturing processes for additional features of the in-house components of 27.5” hard tail cross country sport mountain bicycle family are shown in Appendix A18 and Appendix A19 respectively.

The achieved size tolerance of some in-house components of the 27.5” hard tail cross country sport mountain bicycle families is still higher than the required size tolerance. Therefore, the developed system generates all viable tertiary manufacturing processes to achieve the required size tolerance for some in-house components. The viable and selected tertiary manufacturing process to achieve the required size tolerance is shown in Appendix A20. Meanwhile, the achieved size tolerance of all additional features of the in-house components can be achieved by using the selected primary and secondary processes. Therefore, there is no tertiary manufacturing process required for the additional feature.

Both the main shape and the additional feature of the in-house component of the 27.5" hard tail cross country sport mountain bicycle families do not require fulfilling a certain surface roughness. Therefore, the tertiary manufacturing process to achieve the surface roughness is not generated by the developed system. However, the in-house component requires achieving a certain material property, which is high yield strength. Therefore, the system generates the solution treating and precipitation hardenings process to achieve the required material property.

All the in-house components of the 27.5" hard tail cross country sport mountain bicycle families require an organic finishing process. Based on the requirement, the developed system generates all viable surface finishing processes for each in-house component. Appendix A21 shows the viable and selected surface finishing process for each in-house component of the 27.5" hard tail cross country sport mountain bicycle families. Then, the user must determine whether a basic surface finish is required prior to the required surface finish. The basic surface finish process is a surface finish process that can be conducted prior to the required surface finish process in order to improve the quality of the required surface finish. The viable basic surface finish processes for each in-house component that are generated by the system are polishing and buffing. As the additional features of the in-house components do not require any surface finish, the system does not generate the finishing process for them.

After all manufacturing processes are selected, the user determines whether any cleaning process is required or not for the main shape and the additional feature of the in-house component of 27.5" hard tail cross country sport mountain bicycle families. As the user needs to conduct the basic surface finish process, the developed system generates two cleaning processes, which are a cleaning process prior to the basic surface finish process and prior to the required surface finish process. There is no cleaning process required after the tertiary manufacturing process prior to the polishing and buffing. Appendix A22 shows all viable cleaning processes and the selected cleaning process that must be conducted after the basic surface finish prior to the selected surface finishing process. As explained above, the additional features of the in-house components do not require any surface finish. For that reason, the system does not generate a cleaning process for the additional feature. Finally, the manufacturing process chains for an in-house component and its additional feature are shown in Appendix A23 and Appendix A24.

Next, the developed system calculates the quantity of each outsourced component that needs to be purchased. The system also generates various suppliers for each outsourced component with their region, minimum order, batch order, and price. After that, the user needs to select one of the suppliers to supply each outsourced component. Based on the generated information, the system calculates the quantity of outsourced component orders. Appendix A25 shows the purchased quantity, the selected supplier, and the order quantity for each outsourced component of the 27.5” hard tail cross country sport mountain bicycle families.

Similar to the outsourced component, the developed system also calculates the weight of the required material of in-house component that needs to be purchased. Then, the system generates various suppliers for each required material with their region, minimum order, batch order, and price. After that, the user selects the supplier that is preferred to supply each material. Based on the information, the system calculates the quantity of purchased material orders. Appendix A26 shows the purchased weight, the selected supplier, and the order quantity for each required material with its raw material shape.

Next, the developed system generates the activities consumed by each component, its additional feature, product platform, product variant, taken back product, recovered sub module, and recovered material. The system also generates the department where the activity is conducted, the required resources in the department to conduct the activity, and the required time to conduct the activity. This section only presents one example about the activities and the resources consumed by an in-house component that is generated by the developed system. Appendix A27 shows an example of the activities required by 100 mm Head Tube INS HT 2011 01 component. The required resources in several departments to conduct the activities can be seen in Appendix A28.

6.1.3 Case Study: Calculating Life Cycle Cost

Once all activities have been generated, the developed system generates the activity driver value for each activity, calculates the total time of each activity, and calculates the cost of each activity consumed by the recovered material, the recovered sub module, the component, the product platform, and the product variant. Then, the developed system calculates costs for the recovered material, raw material, material storage, component storage, and outsourced component for each component. For each product platform, the system calculates costs for the recovered sub module, sub module, sub module storage, and product platform storage. After that, the system calculates the costs for the recovered sub module, sub module, sub module storage, product variant storage, taken back product, and taken back product storage for each product variant. Based on the calculated costs, the system calculates the rate of each recovered material, recovered sub module, component, product platform, and product variant. Finally, the system also calculates the cost of each category and the life cycle cost for each component, product platform, and product variant.

This section only presents one example on how the developed system calculates the rate for the in-house component, the product platform and the product variant. The example of the activity driver and the cost of each activity required by the 100 mm Head Tube INS HT 2011 01 component are shown in Appendix A29. Appendix A30 shows various costs and the component rate of the 100 mm Head Tube INS HT 2011 01 component. Various costs and the rate of the 27.5“ Hard Tail XC MTB size 16 product platform and Cozmix CX1.0 27.5 size 16 product variant are shown in Appendix A31 and Appendix A32 respectively. The costs of each category of 100 mm Head Tube INS HT 2011 01 component, 27.5“ Hard Tail XC MTB size 16 product platform, and Cozmix CX1.0 27.5 size 16 product variant, are shown in Appendix A33, Appendix A34, and Appendix A35. Finally, the life cycle cost of the 100 mm Head Tube INS HT 2011 01 component, the 27.5“ Hard Tail XC MTB size 16 product platform, and Cozmix CX1.0 27.5 size 16 product variant are shown in Appendix A36, Appendix A37, and Appendix A38 respectively, to demonstrate the life cycle cost estimation result performed by the system.

6.1.4 Results

The case study shows that the developed system is able to allocate the activity and the resource for each part, product platform, and product variant of different product families. Appendix A27 and Appendix A28 show the example of the activities and the resource allocation of the 100 mm Head Tube INS HT 2011 01 component. Based on the allocation, the system is able to calculate the life cycle cost of each component level of different product families. Appendix A36, Appendix A37, and Appendix A38 show the example of the life cycle cost of the 100 mm Head Tube INS HT 2011 01 component, 27.5“ Hard Tail XC MTB size 16 product platform, and Cozmix CX1.0 27.5 size 16 product variant respectively.

The developed system is able be easily adapted for different companies. If a different approach is used, the user only needs to modify the activity and the time consumed by the activity in the master database. The user interface to modify the activity and the consumed time is shown in Figure 6.13. If different technology is used, the user only needs to modify the resource quantity and the resource rate of the related department in the master database. The user interface to modify the resource quantity and rate of the department is shown in Figure 6.14. By modifying the resource quantity and rate in the master database, the resource capacity cost per time unit required to calculate the cost will be adapted following the new technology. It is not necessary to recollect each resource driver data and its usage. Therefore, it is easy to be modified in order to reflect changes in the operating conditions because it significantly reduces the need for recollecting data. Table 6.6 shows the rate comparison of a component that is manufactured by using different technologies.

The developed system is able to determine the end of life strategy for each sub module of a product family. The end of life strategy for each sub module of a product family and the sub module quantity of each end of life strategy are shown in Appendix A11. In addition, the developed system is also able to determine the end of life strategy for the sub module of a product family that cannot be recovered. The end of life strategy for each unrecovered component and its quantity are shown in Appendix A13. The end of life strategy and its quantity are used to calculate the cost of the recovered material, the unrecovered component, and the recovered sub module. After that, the cost of the recovered material, the unrecovered component, and the recovered sub module are used to calculate the rate of the component, the product platform, and product variant as shown in Appendix A30, Appendix A31, and Appendix A32. Table 6.7 shows how the developed system can be used to assist in comparing the rate of a sub module at different percentage of taken back product.

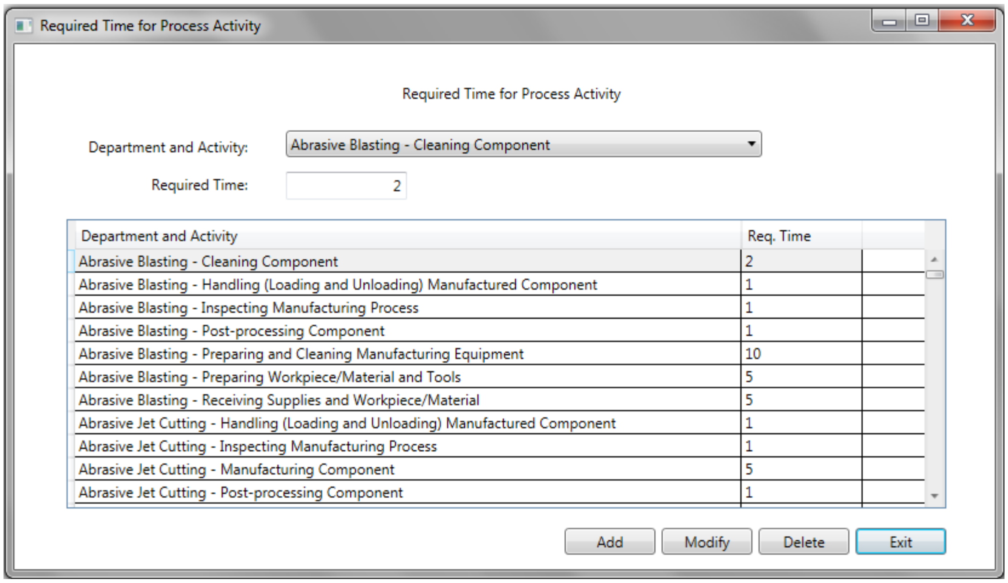

Figure 6.13. User Interface to Modify the Activity and the Consumed Time

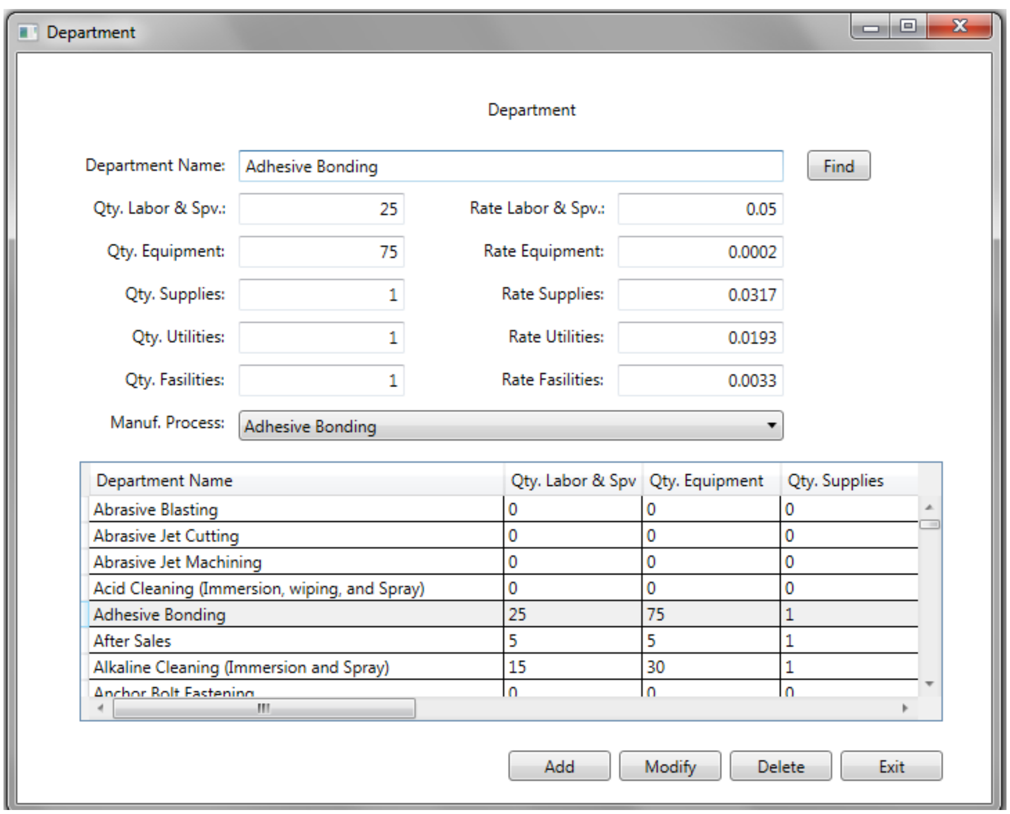

Figure 6.14. User Interface to Modify the Resource Quantity and Rate

Table 6.6. Rate Comparison of 100 mm Head Tube INS HT 2011 01 for Different Technologies

Technology	Recovered Material Cost ($/unit)	Raw Material Cost ($/unit)	Material Storage Cost ($/unit)	Component Storage Cost ($/unit)	Activity Cost ($/unit)	Outsourced Component Cost ($/unit)	Component Rate ($/unit)
Painting – Spray	0	0.324	0.001	0.006	20.63	0	20.961
Painting – Electrode position	0	0.324	0.001	0.006	25.754	0	26.085

Table 6.7. Sub Module Rate Comparison of ALX Alloy Cross Country size 16 for Different Percentage of Taken Back Product

% Taken Back Product	Components Cost ($/unit)	Production Volume (unit)	Recovered Sub Module Cost ($/unit)	Quantity Recovered Sub Module (unit)	Taken Back Sub Module Rate ($/unit)	Sub Module Rate ($/unit)
0	194.09	120000	0	0	0	194.09
50	197.24	60000	0.37	60000	50	123.805

In the case study, two different structures of 27.5“ Hard Tail XC MTB size 16 product family and 27.5“ Hard Tail XC MTB size 18 product family are constructed easily. Figure 6.9 and Figure 6.11demonstrate how to construct different structures of different product families. If a new product structure requires one or more new component, the new component can be updated with less time and effort by storing the component into the master database and then selecting it as the assembled component of the new product structure. Table 6.4 and Table 6.5 demonstrate that the structure of different product variants of a product family is constructed by combining the structure of the product platform and the variants. In addition, the structure of different product platforms and variants is constructed by combining different components. As a result, the life cycle cost of each product variant can be calculated by summing all of its activity costs, the cost of its product platform, the cost of part and outsourced component of its variant, and the storage cost. The life cycle cost of each product platform or variant can be calculated by summing all of its activity costs, the cost of its parts, the storage cost, and the outsourced component cost. To estimate the cost of a new product variant with a different structure, the developed system does not have to recalculate the life cycle cost of the part and the product platform for the new product variant. To estimate the cost of a new product platform with a different structure, the developed system does not have to recalculate the life cycle cost of the part for the new product platform. Therefore, the developed system reduces the time and effort able in estimating the cost of different structures of different product families.

The developed system is able to estimate the life cycle cost at the early stage of product development. The system is able to transform the market segment, the production volume, the product family structure, and the product family function into the required activities and resources information. The market segment and the production volume are shown in Table 6.1. The product family function is shown in Table 6.2 and Table 6.3 and the product structure is shown in Table 6.4 and Table 6.5. These inputs are transformed by the system into the activities and resources information shown in Appendix A27 and Appendix A28.

Based on the cast study, the developed system is able to allocate and then calculate the life cycle cost to each component level of a product family, be easily adapted for different technologies and approaches, determine the end of life strategy for each sub module of a product family, integrate the end of life strategy into the life cycle cost model in order to estimate the life cycle cost of a product family, take into account different structures of different product families and estimate their life cycle cost with less time and effort, and transform the market segment, the production volume, the product family structure, and the product family function into the required activities and resources information. As a conclusion, the developed system is applicable in estimating the life cycle cost of each component level of different product families at the early stage of a product development.

6.2 SUCCESS EVALUATION

The collaborating company has been implementing a tailor-made cost estimation system. As a comparison, Table 6.8 shows the differences between the cost estimation system that is currently used at the collaborating company and the developed cost estimation system. As seen in the table, the main aim of the current system is to estimate the cost of a product variant. It is simple and easy to be used for estimating the cost of similar part or product variant. However, it experiences difficulties in allocating and estimating the life cycle cost of each component level of a product family that consists of a new part of product variant.

Table 6.8. Comparison Current and developed System

Characteristic	Current Cost Estimation System	Developed Cost Estimation System
Estimated Costs	• Each Part Cost • Total Part Cost • Tooling Cost • Assembling Cost • Factory Overhead Cost • Total Cost excluding Import Duty and Tax • Total Cost	• Each Part Cost • Product Platform Cost • Each Product Variant Cost • Recovered Material Cost • Recovered Sub Module Cost • Cost of each Category • Life Cycle Cost
Input	• Model Name • Part Description (Material Code, Manufacturer, Model, Colour, Country of Origin, other Descriptions) • Part Quantity • Estimated Cost Factor of each Part • Other Fees, Charges, Duties, etc.	• Product Family • Product Variant • Module • Module Quantity • Sub Module Option • Product Structure • Various Parameter Data
Technique	• Parts are categorised into different part categories: Frame, Cockpit, Transmission, Wheels, Brakes, Extras • Cost is allocated to different Parts, Assembly Processes, Tools, Factory Overheads, others • Parts Cost (including a new part) is estimated based on the already known or available cost factors • Tooling Cost is estimated based on estimation from its supplier and allocated for each model • Assembly Cost are assumed based on the class of the bicycle (Entry, Medium, High-end) • Other costs are included in a separated Factory Overhead Cost • Calculates the cost of each product variant	• Parts are categorised into different module (functions) • Cost is allocated to different Direct and Indirect Costs of parts and model names • Parts Cost (including a new part) is estimated based on its consumed activity and resources • Tooling Cost and Assembly Cost are not estimated separately but included in Product Variant Cost based on the consumed time • Other costs are included in Part Cost, Product Platform Cost, or Product Variant Cost • Calculates the cost of each component level of a product family

In order to assess the usefulness of the developed time-driven life cycle cost estimation system, the success evaluation is conducted in this research. The flexibility, effectiveness, accuracy, and transparency indicators are used to validate the usefulness of the system because the success evaluation assesses the outcomes that are not directly addressed by the system. For that reason, the Chief Executive Officer of the collaborating company is asked to indicate his ‘level of confidence’ in the flexibility, effectiveness, accuracy, and transparency of the system and then give his/her feedback about the system. The Chief Executive Officer of the collaborating company is selected because he understands not only all the design process in the company but also the financial aspects of the company.

Four questions have been asked to the Chief Executive Officer. The first question asks whether the developed system will be able to take into account various product families and their product variants that are developed at the company. It is used to indicate the level of confidence of the respondent about the flexibility of the system. The second question asks whether the system will be able to help in generating the required information for estimating the cost of various product families and their product variants at the early stage of product development. The answer to the second question indicates the level of confidence of the respondent about the effectiveness of the system. To indicate the level of confidence of the respondent about the transparency of the system, the respondent is asked to answer the third question. The third question asks whether the system will be able to estimate the critical costs of the product families and their product variants in order to perform an evaluation of their design. The fourth question asks whether the system will be able to estimate the cost of the product families and their product variants in an acceptable accuracy for design evaluation. The last question is used to indicate the level of confidence of the respondent about the accuracy of the system. In addition, the Chief Executive Officer has been asked to give any feedback about the system.

Based on his answer, it can be concluded that the developed time-driven life cycle cost estimation system is indicated to be flexible, effective, transparent, and accurate.

6.3 SUMMARY

The case study demonstrates that the developed time-driven life cycle cost estimation system is applicable to achieve the aim and objectives of this research. It is able to allocate and then calculate the life cycle cost to each component level of a product family. The system is easily adapted for different technologies and approaches. In addition, it is able to determine the end of life strategy for each sub module of a product family and integrate the end of life strategy into the life cycle cost model in order to estimate the life cycle cost of a product family. It is also able to take into account different structures of different product families and estimate their life cycle cost with less time and effort. Last, it is able to transform the market segment, the production volume, the product family structure, and the product family function into the required activities and resources information.

Based on the success evaluation, the developed time-driven life cycle cost estimation system is indicated to be flexible, effective, transparent, and accurate. Therefore, the success evaluation shows that the system is indicated to be useful for design evaluation.

As a conclusion, the developed system is validated as an applicable and useful system in estimating the life cycle cost of a product family for design purpose. It is able to estimate the life cycle cost of each component level of different product families by inputting the market segment, the production volume, the product family structure, and the product family function without requiring extensive time and effort in adapting and updating process. In addition, it is expected to give a contribution to practice, especially in helping a company to evaluate the design of a product family.

Chapter 7: Conclusions

This chapter contains the research summary, contributions of this research, and limitations and scope for future research. Section 7.1 reviews the objectives of the research, describes the proposed solution, and explains how the proposed solution can answer the research questions and achieve the objectives. The next section presents various sub-contributions of this research. At the end of this chapter, limitations of this research are outlined and some recommendations for future research are given.

7.1 RESEARCH SUMMARY

It is important to estimate the life cycle cost of each component level of a product family at the early stage of product development. However, the existing systems do not provide satisfying answers for these several problems.

- First, each cost estimation system has its own difficulties in estimating the life cycle cost of each component level of a product family in different types and sizes of companies that use different technologies and approaches.
- Next, the cost estimation system must consider the end of life strategy of the sub module of a product family. In addition, the factors that can be used to determine the end of life of a sub module could be different compared to a product or a part.
- Third, the existing systems are not able or have difficulties to estimate the cost of different product families having different structures.
- Last, the available attributes of a product family at the early stage of product development cannot directly be used to estimate the life cycle cost of a product family. How to use these attributes to estimate the life cycle cost at the early stage of product development has not yet studied. In addition, most of the existing systems do not provide detailed information related to various factors and their influence on the cost.

This research develops a product family design support system, which is able to estimate the life cycle cost of each component level of different product families in different types and sizes of companies that use different technologies and approaches by inputting the market segment, the production volume, the product family structure, and the product family function without requiring extensive time and effort in adapting and updating process. The solutions for the problems above are described below.

- To allocate and calculate the cost of each component level of a product family in different types and sizes of companies that use different technologies and approaches, this research proposes a life cycle cost model adapted from the time-driven activity-based costing technique.
- A method has been developed to determine the end of life strategy of a product family on the sub module level. The end of life strategy is determined and its quantity is modelled based on the component type, the assembly degree of permanence, and the estimated condition of the sub module.
- In order to take into account different structures of different product families, this research proposes that different structures of different products be constructed by combining different assembled components or by combining the same components with different assembly sequences.
- In order to generate the required information to estimate the life cycle cost at the early stage of product development, the knowledge based system is developed in this research. The system transforms the market segment, the production volume, the product family structure, and the product family function into the required activities and resources information.

The developed system has been evaluated by using two types of evaluation, which are application evaluation and success evaluation. Based on the first evaluation, it is shown that the developed system is applicable in complying with the aim and objectives of the research. The second evaluation indicates that the developed system is indicated to be useful and is expected to give a significant contribution to practice, especially to help a company in evaluating the design of a product family.

7.2 CONTRIBUTION OF THIS RESEARCH

This research contributes in the design research area by providing a new design support system that can help a designer in estimating the life cycle cost of each component level of different product families at the early stage of a product development. The system is applicable to estimate the life cycle cost of different product families on the condition that it consists of two or more manufactured products that are assembled from more than one component. In order to provide the main contribution, this research delivers four sub-contributions. The relationship between the research questions, the methodologies, and the contributions of this research is shown in Figure 7.1.

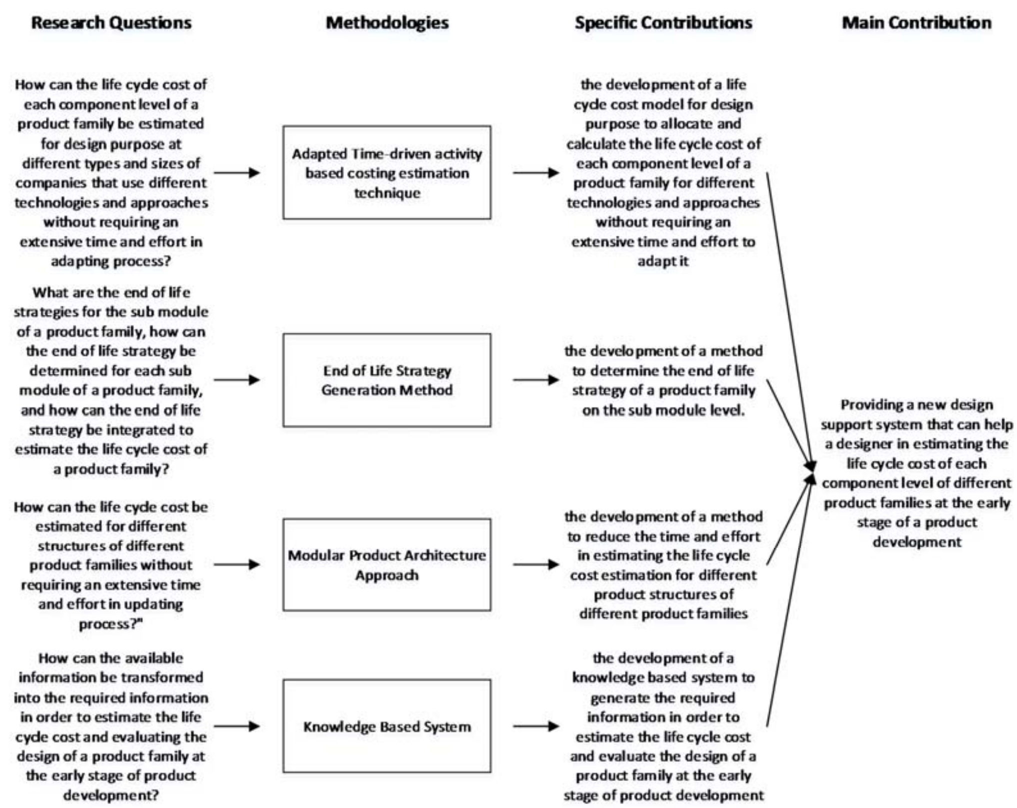

Figure 7.1. Relationship between Research Questions, Methodologies, and Contributions

7.3 LIMITATIONS AND SCOPE FOR FUTURE WORK

This research has accomplished its aim to develop a product family design support system, which is able to estimate the life cycle cost of each component level of different product families in different types and sizes of companies that use different technologies and approaches by inputting the market segment, the production volume, the product family structure, and the product family function, without requiring an extensive time and effort in adapting and updating process. The developed product family design support system has answered the identified research gaps. However, there are some limitations of this thesis due to time and resource constraints. There is also some work that can be done to extend the developed system.

The first limitation is that the developed system is only applicable to estimate the life cycle cost of different discreet manufactured product families. A discrete product family consists of two or more manufactured products that are assembled from more than one component. The component itself is manufactured by using one or more manufacturing processes that can be performed discontinuously.

At this moment, the developed life cycle cost estimation system is not verified because there is not enough data available for verifying the developed system. The collaborating company cannot provide some required data. In addition, none of the existing research provides the sufficient data for conducting system verification.

In the short term, some works are addressed as short extensions of this research work. Even though the validation process shows that the developed system is applicable and useful, the verification process still need to be conducted to make sure that the system conforms to its requirements, for correctness and accuracy. To solve the problem in collecting data, the verification process must be conducted by the collaborating company whenever they are ready to implement the developed system. As they do not need to share the confidential data, it is possible to verify the system. Based on the verification results, then the system could be improved if it is necessary. Next, it would be beneficial to conduct another case study in different types of product family to test the ability of the developed system in handling different situations. As the life cycle cost is recently the most concern in automotive industry, then it is suggested that the next case study is conducted for different car product families. In addition, it would be useful to add a graphical user interface that can present the influence of various factors related to a product family to the life cycle cost of each component level of a product family.

In the long term, other works are also recommended. The data storage process into the master database may still be considered as a time and effort consuming task. Therefore, it is worth finding a way to reduce such effort and time required to build the master database in order to represent, retain, and organise the knowledge. In this case, it is not possible to reduce the amount of the data because the required data must be extended time to time. For that reason, the only way to reduce the time and effort is by using a database technology to assist in storing the re quired data. In addition, the developed life cycle cost model can be the basis to develop an optimisation system. It is recommended to integrate the developed life cycle cost model with an optimisation method for optimising the product family design. Various design parameters of a product family have been identified in this research. The relations between these parameters have been described in the developed life cycle cost model. Then, the key influencing parameters can be optimised to meet the design objectives, such as minimised cost, under given constraints.

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Appendices

Appendix A: Output of System Prototype

Appendix A1. Quantity of Production Runs and Quantity of Product Orders of 27.5” Hard Tail Cross Country Sport MTB Family

Product Family	Product Variant	Production Volume	%Taken Back Product
27.5“ Hard Tail XC MTB size 16	Cozmix CX1.0 27.5 size 16	40,000	50
	Cozmix CX2.0 27.5 size 16	20,000	50
27.5“ Hard Tail XC MTB size 18	Cozmix CX1.0 27.5 size 18	40,000	50
	Cozmix CX2.0 27.5 size 18	20,000	50

Quantity of Production Runs	Quantity of Product Orders
20	4
10	2
20	2
10	2

Appendix A2. Base Module and Its Quantity of 27.5” Hard Tail Cross Country Sport MTB Family

Product Family	Sub Function	Base Module
27.5“ Hard Tail XC MTB size 16	Distribute the rider weight and provides points of attachment for various components	Diamond Frame 11
	Reduce velocity	Hydraulic Disc Brake Set 13
	Convert rotation motion to linear motion	Spoke Wheel Set 83
	Convert rotation motion to linear motion	Spoke Wheel Set 84
	Support the rider	Racing Saddle Set 24
	Change the direction	Flat Bar Steering Set 33
	Provide the brand awareness	Sticker 1
	Provide the brand awareness	Sticker 2
	Stand the bicycle frame	Side Kick Stand Set 1
	Carry various objects	Bottle Cage Set 1
27.5“ Hard Tail XC MTB size 18	Distribute the rider weight and provides points of attachment for various components	Diamond Frame 11
	Reduce velocity	Hydraulic Disc Brake Set 13
	Convert rotation motion to linear motion	Spoke Wheel Set 83
	Convert rotation motion to linear motion	Spoke Wheel Set 84
	Support the rider	Racing Saddle Set 24
	Change the direction	Flat Bar Steering Set 33
	Provide the brand awareness	Sticker 1
	Provide the brand awareness	Sticker 2
	Stand the bicycle frame	Side Kick Stand Set 1
	Carry various objects	Bottle Cage Set 1

Appendix A3. Variant Module and Its Quantity of 27.5” Hard Tail Cross Country Sport MTB Family

Product Variant	Sub Function	Variant Module
Cozmix CX1.0 27.5 size 16	Change the speed ratio	Indexed Trigger Shifter Set 20
	Convert the reciprocating motion into rotational motion	Cotterless Crank Set 33
	Transmit rotation motion	Chain Set 20
	Provide the brand awareness	Badge 1
	Provide the brand awareness	Badge 2
Cozmix CX2.0 27.5 size 16	Change the speed ratio	Indexed Trigger Shifter Set 20
	Convert the reciprocating motion into rotational motion	Cotterless Crank Set 35
	Transmit rotation motion	Chain Set 20
	Provide the brand awareness	Badge 1
	Provide the brand awareness	Badge 2
Cozmix CX1.0 27.5 size 18	Change the speed ratio	Indexed Trigger Shifter Set 20
	Convert the reciprocating motion into rotational motion	Cotterless Crank Set 33
	Transmit rotation motion	Chain Set 20
	Provide the brand awareness	Badge 1
	Provide the brand awareness	Badge 2
Cozmix CX2.0 27.5 size 18	Change the speed ratio	Indexed Trigger Shifter Set 20
	Convert the reciprocating motion into rotational motion	Cotterless Crank Set 35
	Transmit rotation motion	Chain Set 20
	Provide the brand awareness	Badge 1
	Provide the brand awareness	Badge 2

Appendix A4. Selected Sub Module Option for Base Module of 27.5” Hard Tail Cross Country Sport MTB Family

Product Family	Sub Module	Sub Module Option	Quantity
27.5“ Hard Tail XC MTB size 16	Cable Protector	Cable Protector VLZ 034 4mm	2
	Diamond Frame	ALX Alloy Cross Country size 16	1
	Front Hydraulic Disc Brake	Shimano Acera BR-M395 Front Left Brake Set	1
	Rear Hydraulic Disc Brake	Shimano Acera BR-M395 Rear Right Brake Set	1
	Rotor	Shimano SM-RT30 160 mm	2
	27.5" Double Wall Clincher Rim	Araya DM 650 27.5”	2
	Front Axle Skewer	32H Front Axle Skewer	1
	Front Hub	Shimano FH-RM35 Front Hub	1
	Rim Tape	Rim Tape Nylon Red 650B x 20mm	2
	Spoke	Spoke 14G x 270 mm BK	32
	Tube	Schwalbe SV 19	2
	Tube Tire	Schwalbe Smart Sam 27.5”x2.10”	2
	Rear Axle Skewer	32H Rear Axle Skewer	1
	Rear Free Hub	Shimano FH-RM35 Rear Free Hub	1
	Spoke	Spoke 14G x 272 mm BK	32
	Quick Release Seat Clamp	Promax 342Q 34.2QR	1
	Racing Saddle with Bracket Saddle Clamp	Entity Flux Saddle Steel Rail Velo Flux B XC	1
	Rigid Seat Post	Entity Xpert Alloy 30.9x350mm Kalloy SP712N	1
	Coil Spring Suspension Fork	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	1
	Flat Handlebar	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	1
	Handle Grip	Handle Grip VLG1312AD2L Lock	1
	Semi Integrated Head Set	Entity Internal Sealed Bearing Head Set Strummer 1SI110 Caged ϕ28.6	1
	Threadless Stem	Entity Xpert Alloy 90mm CHUN-E IRS-06 ϕ28.6	1
	Sticker SNI	Sticker SNI Poly M Cozmic CX 27.5	1
	Sticker Company	Sticker Insera Sena 5x4 cm	1
	Kick Stand Bracket	Bracket 37-015B-290 M6	1
	Side Kick Stand	Side Kick Stand	1
	Bottle Cage	Bottle Cage	1
	Bottle Cage Bolt	Bottle Bolt TL 230B M5x12	4
27.5“ Hard Tail XC MTB size 18	Cable Protector	Cable Protector VLZ 034 4mm	2
	Diamond Frame	ALX Alloy Cross Country size 18	1
	Front Hydraulic Disc Brake	Shimano Acera BR-M395 Front Left Brake Set	1
	Rear Hydraulic Disc Brake	Shimano Acera BR-M395 Rear Right Brake Set	1
	Rotor	Shimano SM-RT30 160 mm	2
	27.5" Double Wall Clincher Rim	Araya DM 650 27.5”	2

Product Family	Sub Module	Sub Module Option	Quantity
	Front Axle Skewer	32H Front Axle Skewer	1
	Front Hub	Shimano FH-RM35 Front Hub	1
	Rim Tape	Rim Tape Nylon Red 650B x 20mm	2
	Spoke	Spoke 14G x 270 mm BK	32
	Tube	Schwalbe SV 19	2
	Tube Tire	Schwalbe Smart Sam 27.5”x2.10”	2
	Rear Axle Skewer	32H Rear Axle Skewer	1
	Rear Free Hub	Shimano FH-RM35 Rear Free Hub	1
	Spoke	Spoke 14G x 272 mm BK	32
	Quick Release Seat Clamp	Promax 342Q 34.2QR	1
	Racing Saddle with Bracket Saddle Clamp	Entity Flux Saddle Steel Rail Velo Flux B XC	1
	Rigid Seat Post	Entity Xpert Alloy 30.9x350mm Kalloy SP712N	1
	Coil Spring Suspension Fork	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	1
	Flat Handlebar	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	1
	Handle Grip	Handle Grip VLG1312AD2L Lock	2
	Semi Integrated Head Set	Entity Internal Sealed Bearing Head Set Strummer 1SI110 Caged ϕ28.6	1
	Threadless Stem	Entity Xpert Alloy 90mm CHUN-E IRS-06 ϕ28.6	1
	Sticker SNI	Sticker SNI Poly M Cozmic CX 27.5	1
	Sticker Company	Sticker Insera Sena 5x4 cm	1
	Kick Stand Bracket	Bracket 37-015B-290 M6	1
	Side Kick Stand	Side Kick Stand	1
	Bottle Cage	Bottle Cage	1
	Bottle Cage Bolt	Bottle Bolt TL 230B M5x12	4

Appendix A5. Sub Module Option for Variant Module of 27.5” Hard Tail Cross Country Sport MTB Variant

Product Variant	Sub Module	Sub Module Option	Quantity
Cozmix CX1.0 27.5 size 16	Clamp Front Derailleur	Shimano Alivio FD-M430	1
	Front Indexed Trigger Shifter Lever	Front Shimano Alivio SL-M430 3 speed	1
	Rear Indexed Trigger Shifter Lever	Rear Shimano Alivio SL-M430 9 speed	1
	Shifter Cable	Outer Casing OT-40SP	2
	Wide Range Rear Derailleur	Shimano Deore RD-M592SGS	1
	2 pieces Cotterless Crank	Shimano Acera FC-M391 170mm, 42x32x22T	1
	Cartridge Bottom Bracket	Shimano BB-UN26	1
	Quill Pedal	VP Component VP-199	2
	Cassette Rear Sprocket	Shimano CS-HG20, 11-34T 9 Speed	1
	Standard Chain	KMC X-9 PGY 1/2x11/128x110 Links Super Light	1
	Steering Badge	Decal Steering Entity Xpert	1
	Frame Badge	Decal Polygon M Cozmix 1.0 27.5”	1
Cozmix CX2.0 27.5 size 16	Clamp Front Derailleur	Shimano Deore FD-M610	1
	Front Indexed Trigger Shifter Lever	Front Shimano Deore SL-M610 3 speed	1
	Rear Indexed Trigger Shifter Lever	Rear Shimano Deore SL-M610 10 speed	1
	Shifter Cable	Outer Casing OT-40SP	2
	Wide Range Rear Derailleur	Shimano Deore RD-M610SGS	1
	2 pieces Cotterless Crank	Shimano Deore FC-M610, 170mm, 42x32x24T	1
	External Bottom Bracket	Shimano Hollowtech 2	1
	Quill Pedal	VP Component VP-199	2
	Cassette Rear Sprocket	Shimano Deore CS-HG62, 11-36T 10 Speed	1
	Standard Chain	Shimano Deore CN-HG54 1/2" x 11/128", Closing link: Chain Pin, 116 links	1
	Steering Badge	Decal Steering Entity Xpert	1
	Frame Badge	Decal Polygon M Cozmix 2.0 27.5”	1
Cozmix CX1.0 27.5 size 18	Clamp Front Derailleur	Shimano Alivio FD-M430	1
	Front Indexed Trigger Shifter Lever	Front Shimano Alivio SL-M430 3 speed	1
	Rear Indexed Trigger Shifter Lever	Rear Shimano Alivio SL-M430 9 speed	1
	Shifter Cable	Outer Casing OT-40SP	2
	Wide Range Rear Derailleur	Shimano Deore RD-M592SGS	1
	2 pieces Cotterless Crank	Shimano Acera FC-M391 170mm, 42x32x22T	1
	Cartridge Bottom Bracket	Shimano BB-UN26	1
	Quill Pedal	VP Component VP-199	2
	Cassette Rear Sprocket	Shimano CS-HG20, 11-34T 9 Speed	1
	Standard Chain	KMC X-9 PGY 1/2x11/128x110 Links Super Light	1
	Steering Badge	Decal Steering Entity Xpert	1
	Frame Badge	Decal Polygon M Cozmix 1.0	1

Product Variant	Sub Module	Sub Module Option	Quantity
		27.5”	
Cozmix CX2.0 27.5 size 18	Clamp Front Derailleur	Shimano Deore FD-M610	1
	Front Indexed Trigger Shifter Lever	Front Shimano Deore SL-M610 3 speed	1
	Rear Indexed Trigger Shifter Lever	Rear Shimano Deore SL-M610 10 speed	1
	Shifter Cable	Outer Casing OT-40SP	2
	Wide Range Rear Derailleur	Shimano Deore RD-M610SGS	1
	2 pieces Cotterless Crank	Shimano Deore FC-M610, 170mm, 42x32x24T	1
	External Bottom Bracket	Shimano Hollowtech 2	1
	Quill Pedal	VP Component VP-199	2
	Cassette Rear Sprocket	Shimano Deore CS-HG62, 11-36T 10 Speed	1
	Standard Chain	Shimano Deore CN-HG54 1/2" x 11/128", Closing link: Chain Pin, 116 links	1
	Steering Badge	Decal Steering Entity Xpert	1
	Frame Badge	Decal Polygon M Cozmix 2.0 27.5”	1

Appendix A6. Component and Its Attributes of 27.5” Hard Tail Cross Country Sport MTB Variant

Product Variant	Components	Quantity	Procurement Strategy
Cozmix CX1.0 27.5 size 16	Cable Protector VLZ 034 4mm	1	Outsourced
	100 mm Head Tube INS HT 2011 01	1	In-house
	406 mm Seat Tube 35x2.05Tx1.6T 460L	1	In-house
	424 mm Seat Stay INS SS 2011	2	In-house
	425 mm Chain Stay INS CS 2011	2	In-house
	547 mm Top Tube INS TT 2011	1	In-house
	669 mm Down Tube INS DT 2011 01	1	In-house
	Boss Nut VERTECH 46 041B 090	4	Outsourced
	Cable guide C11 101 095 Alloy	7	Outsourced
	Cable guide T12 101 175 2in1	3	Outsourced
	Cable Stopper ALY JS AL3 1P	1	Outsourced
	End Frame INS RE 2012 001 Left	1	Outsourced
	End Frame INS RE 2012 001 Right	1	Outsourced
	ϕ 41 mm Bottom Bracket Shell	1	In-house
	Seat Stay Bracket INS BR 2011	1	Outsourced
	Bracket Shimano Acera BR-M395	1	Outsourced
	Caliper Shimano Acera BR-M395	1	Outsourced
	Front Brake Lever Shimano Acera BR-M395	1	Outsourced
	Hose Shimano Acera BR-M395	1	Outsourced
	Bracket Shimano Acera BR-M395	1	Outsourced
	Caliper Shimano Acera BR-M395	1	Outsourced
	Hose Shimano Acera BR-M395	1	Outsourced
	Rear Brake Lever Shimano Acera BR-M395	1	Outsourced
	Shimano SM-RT30 160 mm	1	Outsourced
	Araya DM 650 27.5"	1	Outsourced
	32H ϕ9 mm l=108 mm Skewer	1	Outsourced
	32H ϕ9 mm Nut	1	Outsourced
	32H Front Spring	2	Outsourced
	Shimano FH-RM35 BL	1	Outsourced
	Rim Tape Nylon Red 650B x 20mm	1	Outsourced
	Eyelet 14G x 270	1	Outsourced
	Nipple 14G x 270	1	Outsourced
	Spoke 14G x 270	1	Outsourced
	Schwalbe SV 19	1	Outsourced
	Schwalbe Smart Sam 27.5”x2.10”	1	Outsourced
	32H ϕ10 mm Nut	1	Outsourced
	32H ϕ10 mm l=145 mmSkewer	1	Outsourced
	32H Rear Spring	2	Outsourced
	Shimano FH-RM35 BZBL	1	Outsourced
	Eyelet 14G x 272	1	Outsourced
	Nipple 14G x 272	1	Outsourced
	Spoke 14G x 272	1	Outsourced
	Promax 342Q 34.2QR	1	Outsourced
	Saddle Steel Rail Velo Flux B XC	1	Outsourced
	Saddle	1	Outsourced
	Entity Xpert Alloy 30.9x350mm Kalloy SP712N	1	Outsourced
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	1	Outsourced
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	1	Outsourced
	Handle Grip VLG1312AD2L Lock	1	Outsourced

Product Variant	Components	Quantity	Procurement Strategy
	Bearing 1SI110	2	Outsourced
	Stem Cap SP 23 BK ϕ28.6	1	Outsourced
	Washer 1SI110 28.6x33x10 mm	2	Outsourced
	Washer 1SI110 28.6x33x5 mm	2	Outsourced
	Entity Expert Alloy 90mm CHUN-E IRS-06 ϕ28.6	1	Outsourced
	Sticker SNI Poly M Cozmic CX 27.5	1	Outsourced
	Sticker Insera Sena 5x4 cm	1	Outsourced
	Bracket 37-015B-290 M6	1	Outsourced
	Side Kick Stand	1	Outsourced
	Bottle Cage	1	Outsourced
	Bottle Bolt TL 230B M5x12	1	Outsourced
	Shimano Alivio FD-M430	1	Outsourced
	Front Shimano Alivio SL-M430 3 speed	1	Outsourced
	Rear Shimano Alivio SL-M430 9 speed	1	Outsourced
	Outer Casing OT-40SP	1	Outsourced
	Shimano Deore RD-M592SGS	1	Outsourced
	Crank Cup Shimano Acera FC-M391 170mm, 42x32x22T	1	Outsourced
	Left Arm Shimano Acera FC-M391 170mm, 42x32x22T	1	Outsourced
	Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	1	Outsourced
	Cartridge Shimano BB-UN26	1	Outsourced
	Lockring Shimano BB-UN26	1	Outsourced
	VP Component VP-199	1	Outsourced
	Shimano CS-HG20, 11-34T 9 Speed	1	Outsourced
	KMC X-9 PGY 1/2x11/128x110 Links Super Light	1	Outsourced
	Decal Steering Entity Xpert	1	Outsourced
	Decal Polygon M Cozmix 1.0 27.5”	1	Outsourced
Cozmix CX2.0 27.5 size 16	Cable Protector VLZ 034 4mm	1	Outsourced
	100 mm Head Tube INS HT 2011 01	1	In-house
	406 mm Seat Tube 35x2.05Tx1.6T 460L	1	In-house
	424 mm Seat Stay INS SS 2011	2	In-house
	425 mm Chain Stay INS CS 2011	2	In-house
	547 mm Top Tube INS TT 2011	1	In-house
	669 mm Down Tube INS DT 2011 01	1	In-house
	Boss Nut VERTECH 46 041B 090	4	Outsourced
	Cable guide C11 101 095 Alloy	7	Outsourced
	Cable guide T12 101 175 2in1	3	Outsourced
	Cable Stopper ALY JS AL3 1P	1	Outsourced
	End Frame INS RE 2012 001 Left	1	Outsourced
	End Frame INS RE 2012 001 Right	1	Outsourced
	ϕ 41 mm Bottom Bracket Shell	1	In-house
	Seat Stay Bracket INS BR 2011	1	Outsourced
	Bracket Shimano Acera BR-M395	1	Outsourced
	Caliper Shimano Acera BR-M395	1	Outsourced
	Front Brake Lever Shimano Acera BR-M395	1	Outsourced
	Hose Shimano Acera BR-M395	1	Outsourced
	Bracket Shimano Acera BR-M395	1	Outsourced
	Caliper Shimano Acera BR-M395	1	Outsourced
	Hose Shimano Acera BR-M395	1	Outsourced
	Rear Brake Lever Shimano Acera BR-M395	1	Outsourced
	Shimano SM-RT30 160 mm	1	Outsourced

Product Variant	Components	Quantity	Procurement Strategy
	Araya DM 650 27.5"	1	Outsourced
	32H ϕ9 mm l=108 mm Skewer	1	Outsourced
	32H ϕ9 mm Nut	1	Outsourced
	32H Front Spring	2	Outsourced
	Shimano FH-RM35 BL	1	Outsourced
	Rim Tape Nylon Red 650B x 20mm	1	Outsourced
	Eyelet 14G x 270	1	Outsourced
	Nipple 14G x 270	1	Outsourced
	Spoke 14G x 270	1	Outsourced
	Schwalbe SV 19	1	Outsourced
	Schwalbe Smart Sam 27.5”x2.10”	1	Outsourced
	32H ϕ10 mm Nut	1	Outsourced
	32H ϕ10 mm l=145 mmSkewer	1	Outsourced
	32H Rear Spring	2	Outsourced
	Shimano FH-RM35 BZBL	1	Outsourced
	Eyelet 14G x 272	1	Outsourced
	Nipple 14G x 272	1	Outsourced
	Spoke 14G x 272	1	Outsourced
	Promax 342Q 34.2QR	1	Outsourced
	Saddle Steel Rail Velo Flux B XC	1	Outsourced
	Saddle	1	Outsourced
	Entity Xpert Alloy 30.9x350mm Kalloy SP712N	1	Outsourced
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	1	Outsourced
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	1	Outsourced
	Handle Grip VLG1312AD2L Lock	1	Outsourced
	Bearing 1SI110	2	Outsourced
	Stem Cap SP 23 BK ϕ28.6	1	Outsourced
	Washer 1SI110 28.6x33x10 mm	2	Outsourced
	Washer 1SI110 28.6x33x5 mm	2	Outsourced
	Entity Expert Alloy 90mm CHUN-E IRS-06 ϕ28.6	1	Outsourced
	Sticker SNI Poly M Cozmic CX 27.5	1	Outsourced
	Sticker Insera Sena 5x4 cm	1	Outsourced
	Bracket 37-015B-290 M6	1	Outsourced
	Side Kick Stand	1	Outsourced
	Bottle Cage	1	Outsourced
	Bottle Bolt TL 230B M5x12	1	Outsourced
	Shimano Deore FD-M610	1	Outsourced
	Shimano Deore SL-M610 3 speed	1	Outsourced
	Shimano Deore SL-M610 10 speed	1	Outsourced
	Outer Casing OT-40SP	1	Outsourced
	Shimano Deore RD-M610SGS	1	Outsourced
	Crank Cup Shimano Deore FC-M610	1	Outsourced
	Left Arm Shimano Deore FC-M610	1	Outsourced
	Right Arm with Spindle Shimano Deore FC-M610	1	Outsourced
	Left Cup Shimano Hollowtech 2	1	Outsourced
	Right Cup and Bearing Shimano Hollowtech 2	1	Outsourced
	VP Component VP-199	1	Outsourced
	Shimano Deore CS-HG62, 11-36T, 10 Speed	1	Outsourced
	Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116	1	Outsourced

Product Variant	Components	Quantity	Procurement Strategy
	links		
	Decal Steering Entity Xpert	1	Outsourced
	Decal Polygon M Cozmix 2.0 27.5”	1	Outsourced
Cozmix CX1.0 27.5 size 18	Cable Protector VLZ 034 4mm	1	Outsourced
	100 mm Head Tube INS HT 2011 01	1	In-house
	425 mm Chain Stay INS CS 2011	2	In-house
	Boss Nut VERTECH 46 041B 090	4	Outsourced
	Cable guide C11 101 095 Alloy	7	Outsourced
	Cable guide T12 101 175 2in1	3	Outsourced
	Cable Stopper ALY JS AL3 1P	1	Outsourced
	End Frame INS RE 2012 001 Left	1	Outsourced
	End Frame INS RE 2012 001 Right	1	Outsourced
	ϕ 41 mm Bottom Bracket Shell	1	In-house
	Seat Stay Bracket INS BR 2011	1	Outsourced
	457 mm Seat Tube 35x2.05Tx1.6T 460L	1	In-house
	512 mm Seat Stay INS SS 2011	2	In-house
	561 mm Top Tube INS TT 2011	1	In-house
	690 mm Down Tube INS DT 2011 01	1	In-house
	Bracket Shimano Acera BR-M395	1	Outsourced
	Caliper Shimano Acera BR-M395	1	Outsourced
	Front Brake Lever Shimano Acera BR-M395	1	Outsourced
	Hose Shimano Acera BR-M395	1	Outsourced
	Bracket Shimano Acera BR-M395	1	Outsourced
	Caliper Shimano Acera BR-M395	1	Outsourced
	Hose Shimano Acera BR-M395	1	Outsourced
	Rear Brake Lever Shimano Acera BR-M395	1	Outsourced
	Shimano SM-RT30 160 mm	1	Outsourced
	Araya DM 650 27.5"	1	Outsourced
	32H ϕf9 mm l=108 mm Skewer	1	Outsourced
	32H ϕ9 mm Nut	1	Outsourced
	32H Front Spring	2	Outsourced
	Shimano FH-RM35 BL	1	Outsourced
	Rim Tape Nylon Red 650B x 20mm	1	Outsourced
	Eyelet 14G x 270	1	Outsourced
	Nipple 14G x 270	1	Outsourced
	Spoke 14G x 270	1	Outsourced
	Schwalbe SV 19	1	Outsourced
	Schwalbe Smart Sam 27.5”x2.10”	1	Outsourced
	32H ϕ10 mm Nut	1	Outsourced
	32H ϕ10 mm l=145 mm Skewer	1	Outsourced
	32H Rear Spring	2	Outsourced
	Shimano FH-RM35 BZBL	1	Outsourced
	Eyelet 14G x 272	1	Outsourced
	Nipple 14G x 272	1	Outsourced
	Spoke 14G x 272	1	Outsourced
	Promax 342Q 34.2QR	1	Outsourced
	Saddle Steel Rail Velo Flux B XC	1	Outsourced
	Saddle	1	Outsourced
	Entity Xpert Alloy 30.9x350mm Kalloy SP712N	1	Outsourced
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	1	Outsourced
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	1	Outsourced
	Handle Grip VLG1312AD2L Lock	1	Outsourced
	Bearing 1SI110	2	Outsourced

Product Variant	Components	Quantity	Procurement Strategy
	Stem Cap SP 23 BK ϕ28.6	1	Outsourced
	Washer 1SI110 28.6x33x10 mm	2	Outsourced
	Washer 1SI110 28.6x33x5 mm	2	Outsourced
	Entity Expert Alloy 90mm CHUN-E IRS-06 ϕ28.6	1	Outsourced
	Sticker SNI Poly M Cozmic CX 27.5	1	Outsourced
	Sticker Insera Sena 5x4 cm	1	Outsourced
	Bracket 37-015B-290 M6	1	Outsourced
	Side Kick Stand	1	Outsourced
	Bottle Cage	1	Outsourced
	Bottle Bolt TL 230B M5x12	1	Outsourced
	Shimano Alivio FD-M430	1	Outsourced
	Front Shimano Alivio SL-M430 3 speed	1	Outsourced
	Rear Shimano Alivio SL-M430 9 speed	1	Outsourced
	Outer Casing OT-40SP	1	Outsourced
	Shimano Deore RD-M592SGS	1	Outsourced
	Crank Cup Shimano Acera FC-M391 170mm, 42x32x22T	1	Outsourced
	Left Arm Shimano Acera FC-M391 170mm, 42x32x22T	1	Outsourced
	Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	1	Outsourced
	Cartridge Shimano BB-UN26	1	Outsourced
	Lockring Shimano BB-UN26	1	Outsourced
	VP Component VP-199	1	Outsourced
	Shimano CS-HG20, 11-34T 9 Speed	1	Outsourced
	KMC X-9 PGY 1/2x11/128x110 Links Super Light	1	Outsourced
	Decal Steering Entity Xpert	1	Outsourced
	Decal Polygon M Cozmix 1.0 27.5"	1	Outsourced
Cozmix CX2.0 27.5 size 18	Cable Protector VLZ 034 4mm	1	Outsourced
	100 mm Head Tube INS HT 2011 01	1	In-house
	425 mm Chain Stay INS CS 2011	2	In-house
	Boss Nut VERTECH 46 041B 090	4	Outsourced
	Cable guide C11 101 095 Alloy	7	Outsourced
	Cable guide T12 101 175 2in1	3	Outsourced
	Cable Stopper ALY JS AL3 1P	1	Outsourced
	End Frame INS RE 2012 001 Left	1	Outsourced
	End Frame INS RE 2012 001 Right	1	Outsourced
	ϕ 41 mm Bottom Bracket Shell	1	In-house
	Seat Stay Bracket INS BR 2011	1	Outsourced
	457 mm Seat Tube 35x2.05Tx1.6T 460L	1	In-house
	512 mm Seat Stay INS SS 2011	2	In-house
	561 mm Top Tube INS TT 2011	1	In-house
	690 mm Down Tube INS DT 2011 01	1	In-house
	Bracket Shimano Acera BR-M395	1	Outsourced
	Caliper Shimano Acera BR-M395	1	Outsourced
	Front Brake Lever Shimano Acera BR-M395	1	Outsourced
	Hose Shimano Acera BR-M395	1	Outsourced
	Bracket Shimano Acera BR-M395	1	Outsourced
	Caliper Shimano Acera BR-M395	1	Outsourced
	Hose Shimano Acera BR-M395	1	Outsourced
	Rear Brake Lever Shimano Acera BR-M395	1	Outsourced
	Shimano SM-RT30 160 mm	1	Outsourced
	Araya DM 650 27.5"	1	Outsourced
	32H ϕ9 mm l=108 mm Skewer	1	Outsourced

Product Variant	Components	Quantity	Procurement Strategy
	32H ϕ9 mm Nut	1	Outsourced
	32H Front Spring	2	Outsourced
	Shimano FH-RM35 BL	1	Outsourced
	Rim Tape Nylon Red 650B x 20mm	1	Outsourced
	Eyelet 14G x 270	1	Outsourced
	Nipple 14G x 270	1	Outsourced
	Spoke 14G x 270	1	Outsourced
	Schwalbe SV 19	1	Outsourced
	Schwalbe Smart Sam 27.5”x2.10”	1	Outsourced
	32H ϕ10 mm Nut	1	Outsourced
	32H ϕ10 mm l=145 mmSkewer	1	Outsourced
	32H Rear Spring	2	Outsourced
	Shimano FH-RM35 BZBL	1	Outsourced
	Eyelet 14G x 272	1	Outsourced
	Nipple 14G x 272	1	Outsourced
	Spoke 14G x 272	1	Outsourced
	Promax 342Q 34.2QR	1	Outsourced
	Saddle Steel Rail Velo Flux B XC	1	Outsourced
	Saddle	1	Outsourced
	Entity Xpert Alloy 30.9x350mm Kalloy SP712N	1	Outsourced
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	1	Outsourced
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	1	Outsourced
	Handle Grip VLG1312AD2L Lock	1	Outsourced
	Bearing 1SI110	2	Outsourced
	Stem Cap SP 23 BK ϕ28.6	1	Outsourced
	Washer 1SI110 28.6x33x10 mm	2	Outsourced
	Washer 1SI110 28.6x33x5 mm	2	Outsourced
	Entity Expert Alloy 90mm CHUN-E IRS-06 ϕ28.6	1	Outsourced
	Sticker SNI Poly M Cozmic CX 27.5	1	Outsourced
	Sticker Insera Sena 5x4 cm	1	Outsourced
	Bracket 37-015B-290 M6	1	Outsourced
	Side Kick Stand	1	Outsourced
	Bottle Cage	1	Outsourced
	Bottle Bolt TL 230B M5x12	1	Outsourced
	Shimano Deore FD-M610	1	Outsourced
	Shimano Deore SL-M610 3 speed	1	Outsourced
	Shimano Deore SL-M610 10 speed	1	Outsourced
	Outer Casing OT-40SP	1	Outsourced
	Shimano Deore RD-M610SGS	1	Outsourced
	Crank Cup Shimano Deore FC-M610	1	Outsourced
	Left Arm Shimano Deore FC-M610	1	Outsourced
	Right Arm with Spindle Shimano Deore FC-M610	1	Outsourced
	Left Cup Shimano Hollowtech 2	1	Outsourced
	Right Cup and Bearing Shimano Hollowtech 2	1	Outsourced
	VP Component VP-199	1	Outsourced
	Shimano Deore CS-HG62, 11-36T, 10 Speed	1	Outsourced
	Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116 links	1	Outsourced
	Decal Steering Entity Xpert	1	Outsourced
	Decal Polygon M Cozmix 2.0 27.5”	1	Outsourced

Appendix A7. Attributes of In-house Component of 27.5” Hard Tail Cross Country Sport MTB Family

In-house Component	Material	Basic Shape	Shape Complexity
100 mm Head Tube INS HT 2011 01	Aluminium Alloy	Round	Hollow/Cut Outs Through
406 mm Seat Tube 35x2.05Tx1.6T 460L	Aluminium Alloy	Round	Hollow/Cut Outs Through
424 mm Seat Stay INS SS 2011	Aluminium Alloy	Tapered Oval	Hollow/Cut Outs Through
425 mm Chain Stay INS CS 2011	Aluminium Alloy	Tapered Polygon	Hollow/Cut Outs Through
457 mm Seat Tube 35x2.05Tx1.6T 460L	Aluminium Alloy	Round	Hollow/Cut Outs Through
512 mm Seat Stay INS SS 2011	Aluminium Alloy	Tapered Oval	Hollow/Cut Outs Through
547 mm Top Tube INS TT 2011	Aluminium Alloy	Tapered Polygon	Hollow/Cut Outs Through
561 mm Top Tube INS TT 2011	Aluminium Alloy	Tapered Polygon	Hollow/Cut Outs Through
669 mm Down Tube INS DT 2011 01	Aluminium Alloy	Tapered Polygon	Hollow/Cut Outs Through
690 mm Down Tube INS DT 2011 01	Aluminium Alloy	Tapered Polygon	Hollow/Cut Outs Through
ϕ41 mm Bottom Bracket Shell	Aluminium Alloy	Round	Hollow/Cut Outs Through

Shape Complexity Type	Diameter	Length	Width	Thickness	Height	Weight
Stepped / Contoured	5.00	10.00	N/A	0.20	N/A	0.08
Uniform Cross Section	4.10	40.60	N/A	0.20	N/A	0.28
Spatial Curvature	3.00	42.40	N/A	0.20	N/A	0.20
Stepped / Contoured	3.50	42.50	N/A	0.20	N/A	0.24
Uniform Cross Section	4.10	45.70	N/A	0.20	N/A	0.30
Spatial Curvature	3.00	51.20	N/A	0.20	N/A	0.24
Uniform Cross Section	5.00	54.70	N/A	0.20	N/A	0.47
Uniform Cross Section	5.00	56.10	N/A	0.20	N/A	0.45
Spatial Curvature	6.00	66.90	N/A	0.20	N/A	0.65
Spatial Curvature	6.00	69.00	N/A	0.20	N/A	0.68
Uniform Cross Section	4.10	7.30	N/A	0.20	N/A	0.05

Size Tolerance	Surface Roughness	Material Property	Surface Finish
0.20	N/A	High Yield Strength	Organic Finished
0.05	N/A	High Yield Strength	Organic Finished
0.05	N/A	High Yield Strength	Organic Finished
0.05	N/A	High Yield Strength	Organic Finished
0.05	N/A	High Yield Strength	Organic Finished
0.05	N/A	High Yield Strength	Organic Finished
0.05	N/A	High Yield Strength	Organic Finished
0.05	N/A	High Yield Strength	Organic Finished
0.05	N/A	High Yield Strength	Organic Finished
0.05	N/A	High Yield Strength	Organic Finished
0.20	N/A	High Yield Strength	Organic Finished

Appendix A8. Attributes of Additional Feature of In-house Component

In-house Component	Additional Feature Type	Additional Feature Name	Quantity
406 mm Seat Tube 35x2.05Tx1.6T 460L	Subtractive: Radial Holes	Seat Tube Hole 1	2
457 mm Seat Tube 35x2.05Tx1.6T 460L	Subtractive: Radial Holes	Seat Tube Hole 2	2
669 mm Down Tube INS DT 2011 01	Subtractive: Radial Holes	Down Tube Hole 1	2
690 mm Down Tube INS DT 2011 01	Subtractive: Radial Holes	Down Tube Hole 2	2

Diameter	Length	Width	Thickness	Height
5.00	12.00	N/A	N/A	N/A
5.00	12.00	N/A	N/A	N/A
5.00	12.00	N/A	N/A	N/A
5.00	12.00	N/A	N/A	N/A

Size Tolerance	Surface Roughness	Surface Finish
N/A	N/A	N/A
N/A	N/A	N/A
N/A	N/A	N/A
N/A	N/A	N/A

Appendix A9. Assembly Method and Joining Process of each Component Assembly Sequence for Product Platform of 27.5” Hard Tail Cross Country Sport MTB Family

Product Family	Assembled Components		Assembly Method	Joining Process	Assembly Compl. Coeff.
	1st Component	2nd Component			
27.5“ Hard Tail XC MTB size 16	406 mm Seat Tube 35x2.05Tx1.6T 460L	Boss Nut VERTECH 46 041B 090	Dedicated	Threaded Fastening	1
	406 mm Seat Tube 35x2.05Tx1.6T 460L	Cable Stopper ALY JS AL3 1P	Dedicated	Gas Tungsten Arc Welding	1
	ϕ 41 mm Bottom Bracket Shell	406 mm Seat Tube 35x2.05Tx1.6T 460L	Dedicated	Gas Tungsten Arc Welding	1
	669 mm Down Tube INS DT 2011 01	Boss Nut VERTECH 46 041B 090	Dedicated	Threaded Fastening	1
	669 mm Down Tube INS DT 2011 01	Cable guide C11 101 095 Alloy	Dedicated	Plasma Arc Welding	1
	100 mm Head Tube INS HT 2011 01	669 mm Down Tube INS DT 2011 01	Dedicated	Gas Tungsten Arc Welding	1
	ϕ 41 mm Bottom Bracket Shell	669 mm Down Tube INS DT 2011 01	Dedicated	Gas Tungsten Arc Welding	1
	547 mm Top Tube INS TT 2011	Cable guide T12 101 175 2in1	Dedicated	Plasma Arc Welding	1
	406 mm Seat Tube 35x2.05Tx1.6T 460L	547 mm Top Tube INS TT 2011	Dedicated	Gas Tungsten Arc Welding	1
	100 mm Head Tube INS HT 2011 01	547 mm Top Tube INS TT 2011	Dedicated	Gas Tungsten Arc Welding	1
	425 mm Chain Stay INS CS 2011	Cable guide C11 101 095 Alloy	Dedicated	Plasma Arc Welding	1
	425 mm Chain Stay INS CS 2011	End Frame INS RE 2012 001 Right	Dedicated	Gas Tungsten Arc Welding	1
	425 mm Chain Stay INS CS 2011	End Frame INS RE 2012 001 Left	Dedicated	Gas Tungsten Arc Welding	1
	ϕ 41 mm Bottom Bracket Shell	425 mm Chain Stay INS CS 2011	Dedicated	Plasma Arc Welding	1
	424 mm Seat Stay INS SS 2011	Cable guide C11 101 095 Alloy	Dedicated	Plasma Arc Welding	1
	406 mm Seat Tube 35x2.05Tx1.6T 460L	424 mm Seat Stay INS SS 2011	Dedicated	Plasma Arc Welding	1
	424 mm Seat Stay INS SS 2011	Seat Stay Bracket INS BR 2011	Dedicated	Gas Tungsten Arc Welding	1
	425 mm Chain Stay INS CS 2011	424 mm Seat Stay INS SS 2011	Dedicated	Plasma Arc Welding	1
	406 mm Seat Tube 35x2.05Tx1.6T 460L	Promax 342Q 34.2QR	Dedicated	Quick Release Fastening	1
	406 mm Seat Tube 35x2.05Tx1.6T 460L	Sticker SNI Poly M Cozmic CX 27.5	Dedicated	Adhesive Bonding	1
	406 mm Seat Tube 35x2.05Tx1.6T 460L	Sticker Insera Sena 5x4 cm	Dedicated	Adhesive Bonding	1
	669 mm Down Tube INS DT 2011 01	Decal Polygon M Cozmix 1.0 27.5”	Dedicated	Adhesive Bonding	1
	100 mm Head Tube	Bearing 1SI110	Dedicated	Non-Joining	1

Product	Assembled Components		Assembly	Joining	Assembly
	INS HT 2011 01			Assembling	
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x5 mm	Dedicated	Non-Joining Assembling	1
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x10 mm	Dedicated	Non-Joining Assembling	1
	Bearing 1SI110	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Dedicated	Non-Joining Assembling	1
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x5 mm	Dedicated	Non-Joining Assembling	1
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x10 mm	Dedicated	Non-Joining Assembling	1
	100 mm Head Tube INS HT 2011 01	Stem Cap SP 23 BK ϕ28.6	Dedicated	Threaded Fastening	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Handle Grip VLG1312AD2L Lock	Dedicated	Shrink Fitting	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Front Brake Lever Shimano Acera BR-M395	Dedicated	Threaded Fastening	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Rear Brake Lever Shimano Acera BR-M395	Dedicated	Threaded Fastening	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Entity Expert Alloy 90mm CHUN-E IRS-06 ϕ28.6	Dedicated	Threaded Fastening	1
	Shimano FH-RM35 BL	Spoke 14G x 270	Dedicated	Non-Joining Assembling	1
	Araya DM 650 27.5"	Eyelet 14G x 270	Dedicated	Non-Joining Assembling	1
	Eyelet 14G x 270	Spoke 14G x 270	Dedicated	Non-Joining Assembling	1
	Eyelet 14G x 270	Nipple 14G x 270	Dedicated	Threaded Fastening	1
	Araya DM 650 27.5"	Rim Tape Nylon Red 650B x 20mm	Dedicated	Shrink Fitting	1
	Araya DM 650 27.5"	Schwalbe SV 19	Dedicated	Shrink Fitting	1
	Araya DM 650 27.5"	Schwalbe Smart Sam 27.5”x2.10”	Dedicated	Shrink Fitting	1
	Shimano FH-RM35 BL	Shimano SM-RT30 160 mm	Dedicated	Threaded Fastening	1
	Araya DM 650 27.5"	32H ϕ9 mm l=108 mm Skewer	Dedicated	Non-Joining Assembling	1
	32H ϕ9 mm l=108 mm Skewer	32H Front Spring	Dedicated	Non-Joining Assembling	1
	32H ϕ9 mm l=108 mm Skewer	32H ϕ9 mm Nut	Dedicated	Threaded Fastening	1
	SR Suntour XCM HLO Travel 100mm	Bracket Shimano Acera BR-M395	Dedicated	Threaded Fastening	1

Product	Assembled Components		Assembly	Joining	Assembly
	1-1/8" Steerer				
	Bracket Shimano Acera BR-M395	Caliper Shimano Acera BR-M395	Dedicated	Threaded Fastening	1
	Caliper Shimano Acera BR-M395	Hose Shimano Acera BR-M395	Dedicated	Threaded Inserts Fastening	1
	Front Brake Lever Shimano Acera BR-M395	Hose Shimano Acera BR-M395	Dedicated	Threaded Inserts Fastening	1
	Saddle Steel Rail Velo Flux B XC	Saddle	Dedicated	Threaded Fastening	1
	Entity Xpert Alloy 30.9x350mm Kalloy SP712N	Saddle Steel Rail Velo Flux B XC	Dedicated	Threaded Fastening	1
	ϕ 41 mm Bottom Bracket Shell	Bracket 37-015B-290 M6	Dedicated	Threaded Fastening	1
	Bracket 37-015B-290 M6	Side Kick Stand	Dedicated	Threaded Fastening	1
	Bottle Cage	Bottle Bolt TL 230B M5x12	Dedicated	Threaded Fastening	1
	Boss Nut VERTECH 46 041B 090	Bottle Bolt TL 230B M5x12	Dedicated	Threaded Fastening	1
	Shimano FH-RM35 BZBL	Spoke 14G x 272	Dedicated	Non-Joining Assembling	1
	Araya DM 650 27.5"	Eyelet 14G x 272	Dedicated	Non-Joining Assembling	1
	Eyelet 14G x 272	Spoke 14G x 272	Dedicated	Non-Joining Assembling	1
	Eyelet 14G x 272	Nipple 14G x 272	Dedicated	Threaded Fastening	1
	Araya DM 650 27.5"	Rim Tape Nylon Red 650B x 20mm	Dedicated	Shrink Fitting	1
	Araya DM 650 27.5"	Schwalbe SV 19	Dedicated	Shrink Fitting	1
	Araya DM 650 27.5"	Schwalbe Smart Sam 27.5"x2.10"	Dedicated	Shrink Fitting	1
	Shimano FH-RM35 BZBL	Shimano SM-RT30 160 mm	Dedicated	Threaded Fastening	1
	424 mm Seat Stay INS SS 2011	Bracket Shimano Acera BR-M395	Dedicated	Threaded Fastening	1
	Bracket Shimano Acera BR-M395	Caliper Shimano Acera BR-M395	Dedicated	Threaded Fastening	1
	Caliper Shimano Acera BR-M395	Hose Shimano Acera BR-M395	Dedicated	Threaded Inserts Fastening	1
	Rear Brake Lever Shimano Acera BR-M395	Hose Shimano Acera BR-M395	Dedicated	Threaded Inserts Fastening	1
27.5" Hard Tail XC MTB size 18	457 mm Seat Tube 35x2.05Tx1.6T 460L	Boss Nut VERTECH 46 041B 090	Dedicated	Threaded Fastening	1
	457 mm Seat Tube 35x2.05Tx1.6T 460L	Cable Stopper ALY JS AL3 1P	Dedicated	Gas Tungsten Arc Welding	1
	ϕ 41 mm Bottom Bracket Shell	457 mm Seat Tube 35x2.05Tx1.6T 460L	Dedicated	Gas Tungsten Arc Welding	1
	690 mm Down Tube	Boss Nut VERTECH	Dedicated	Threaded	1

Product	Assembled Components		Assembly	Joining	Assembly
	INS DT 2011 01	46 041B 090		Fastening	
	690 mm Down Tube INS DT 2011 01	Cable guide C11 101 095 Alloy	Dedicated	Plasma Arc Welding	1
	100 mm Head Tube INS HT 2011 01	690 mm Down Tube INS DT 2011 01	Dedicated	Gas Tungsten Arc Welding	1
	ϕ 41 mm Bottom Bracket Shell	690 mm Down Tube INS DT 2011 01	Dedicated	Gas Tungsten Arc Welding	1
	561 mm Top Tube INS TT 2011	Cable guide T12 101 175 2in1	Dedicated	Plasma Arc Welding	1
	457 mm Seat Tube 35x2.05Tx1.6T 460L	561 mm Top Tube INS TT 2011	Dedicated	Gas Tungsten Arc Welding	1
	100 mm Head Tube INS HT 2011 01	561 mm Top Tube INS TT 2011	Dedicated	Gas Tungsten Arc Welding	1
	425 mm Chain Stay INS CS 2011	Cable guide C11 101 095 Alloy	Dedicated	Plasma Arc Welding	1
	425 mm Chain Stay INS CS 2011	End Frame INS RE 2012 001 Right	Dedicated	Gas Tungsten Arc Welding	1
	425 mm Chain Stay INS CS 2011	End Frame INS RE 2012 001 Left	Dedicated	Gas Tungsten Arc Welding	1
	ϕ 41 mm Bottom Bracket Shell	425 mm Chain Stay INS CS 2011	Dedicated	Plasma Arc Welding	1
	512 mm Seat Stay INS SS 2011	Cable guide C11 101 095 Alloy	Dedicated	Plasma Arc Welding	1
	457 mm Seat Tube 35x2.05Tx1.6T 460L	512 mm Seat Stay INS SS 2011	Dedicated	Plasma Arc Welding	1
	512 mm Seat Stay INS SS 2011	Seat Stay Bracket INS BR 2011	Dedicated	Gas Tungsten Arc Welding	1
	425 mm Chain Stay INS CS 2011	512 mm Seat Stay INS SS 2011	Dedicated	Plasma Arc Welding	1
	457 mm Seat Tube 35x2.05Tx1.6T 460L	Promax 342Q 34.2QR	Dedicated	Quick Release Fastening	1
	457 mm Seat Tube 35x2.05Tx1.6T 460L	Sticker SNI Poly M Cozmic CX 27.5	Dedicated	Adhesive Bonding	1
	457 mm Seat Tube 35x2.05Tx1.6T 460L	Sticker Insera Sena 5x4 cm	Dedicated	Adhesive Bonding	1
	690 mm Down Tube INS DT 2011 01	Decal Polygon M Cozmix 1.0 27.5”	Dedicated	Adhesive Bonding	1
	100 mm Head Tube INS HT 2011 01	Bearing 1SI110	Dedicated	Non-Joining Assembling	1
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x5 mm	Dedicated	Non-Joining Assembling	1
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x10 mm	Dedicated	Non-Joining Assembling	1
	Bearing 1SI110	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Dedicated	Non-Joining Assembling	1
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x5 mm	Dedicated	Non-Joining Assembling	1
	100 mm Head Tube INS HT 2011 01	Washer 1SI110 28.6x33x10 mm	Dedicated	Non-Joining Assembling	1
	100 mm Head Tube INS HT 2011 01	Stem Cap SP 23 BK ϕ28.6	Dedicated	Threaded Fastening	1
	Entity Xpert Alloy	Handle Grip	Dedicated	Shrink Fitting	1

Product	Assembled Components		Assembly	Joining	Assembly
	680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	VLG1312AD2L Lock			
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Front Brake Lever Shimano Acera BR-M395	Dedicated	Threaded Fastening	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Rear Brake Lever Shimano Acera BR-M395	Dedicated	Threaded Fastening	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Entity Expert Alloy 90mm CHUN-E IRS-06 ϕ28.6	Dedicated	Threaded Fastening	1
	Shimano FH-RM35 BL	Spoke 14G x 270	Dedicated	Non-Joining Assembling	1
	Araya DM 650 27.5"	Eyelet 14G x 270	Dedicated	Non-Joining Assembling	1
	Eyelet 14G x 270	Spoke 14G x 270	Dedicated	Non-Joining Assembling	1
	Eyelet 14G x 270	Nipple 14G x 270	Dedicated	Threaded Fastening	1
	Araya DM 650 27.5"	Rim Tape Nylon Red 650B x 20mm	Dedicated	Shrink Fitting	1
	Araya DM 650 27.5"	Schwalbe SV 19	Dedicated	Shrink Fitting	1
	Araya DM 650 27.5"	Schwalbe Smart Sam 27.5”x2.10”	Dedicated	Shrink Fitting	1
	Shimano FH-RM35 BL	Shimano SM-RT30 160 mm	Dedicated	Threaded Fastening	1
	Araya DM 650 27.5"	32H ϕ9 mm l=108 mm Skewer	Dedicated	Non-Joining Assembling	1
	32H ϕ9 mm l=108 mm Skewer	32H Front Spring	Dedicated	Non-Joining Assembling	1
	32H ϕ9 mm l=108 mm Skewer	32H ϕ9 mm Nut	Dedicated	Threaded Fastening	1
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Bracket Shimano Acera BR-M395	Dedicated	Threaded Fastening	1
	Bracket Shimano Acera BR-M395	Caliper Shimano Acera BR-M395	Dedicated	Threaded Fastening	1
	Caliper Shimano Acera BR-M395	Hose Shimano Acera BR-M395	Dedicated	Threaded Inserts Fastening	1
	Front Brake Lever Shimano Acera BR-M395	Hose Shimano Acera BR-M395	Dedicated	Threaded Inserts Fastening	1
	Saddle Steel Rail Velo Flux B XC	Saddle	Dedicated	Threaded Fastening	1
	Entity Xpert Alloy 30.9x350mm Kalloy SP712N	Saddle Steel Rail Velo Flux B XC	Dedicated	Threaded Fastening	1
	ϕ 41 mm Bottom	Bracket 37-015B-290	Dedicated	Threaded	1

Product	Assembled Components		Assembly	Joining	Assembly
	Bracket Shell	M6		Fastening	
	Bracket 37-015B-290 M6	Side Kick Stand	Dedicated	Threaded Fastening	1
	Bottle Cage	Bottle Bolt TL 230B M5x12	Dedicated	Threaded Fastening	1
	Boss Nut VERTECH 46 041B 090	Bottle Bolt TL 230B M5x12	Dedicated	Threaded Fastening	1
	Shimano FH-RM35 BZBL	Spoke 14G x 272	Dedicated	Non-Joining Assembling	1
	Araya DM 650 27.5"	Eyelet 14G x 272	Dedicated	Non-Joining Assembling	1
	Eyelet 14G x 272	Spoke 14G x 272	Dedicated	Non-Joining Assembling	1
	Eyelet 14G x 272	Nipple 14G x 272	Dedicated	Threaded Fastening	1
	Araya DM 650 27.5"	Rim Tape Nylon Red 650B x 20mm	Dedicated	Shrink Fitting	1
	Araya DM 650 27.5"	Schwalbe SV 19	Dedicated	Shrink Fitting	1
	Araya DM 650 27.5"	Schwalbe Smart Sam 27.5”x2.10”	Dedicated	Shrink Fitting	1
	Shimano FH-RM35 BZBL	Shimano SM-RT30 160 mm	Dedicated	Threaded Fastening	1
	512 mm Seat Stay INS SS 2011	Bracket Shimano Acera BR-M395	Dedicated	Threaded Fastening	1
	Bracket Shimano Acera BR-M395	Caliper Shimano Acera BR-M395	Dedicated	Threaded Fastening	1
	Caliper Shimano Acera BR-M395	Hose Shimano Acera BR-M395	Dedicated	Threaded Inserts Fastening	1
	Rear Brake Lever Shimano Acera BR-M395	Hose Shimano Acera BR-M395	Dedicated	Threaded Inserts Fastening	1

Appendix A10. Assembly Method and Joining Process of each Component Assembly Sequence for Variant of 27.5” Hard Tail Cross Country Sport MTB Variant

Product Variant	Assembled Components		Assembly Method	Joining Process	Assembly Compl. Coeff.
	1st Component	2nd Component			
Cozmix CX1.0 27.5 size 16	669 mm Down Tube INS DT 2011 01	Decal Polygon M Cozmix 1.0 27.5”	Dedicated	Adhesive Bonding	1
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Decal Steering Entity Xpert	Dedicated	Adhesive Bonding	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Front Shimano Alivio SL-M430 3 speed	Dedicated	Threaded Fastening	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Rear Shimano Alivio SL-M430 9 speed	Dedicated	Threaded Fastening	1
	Front Shimano Alivio SL-M430 3 speed	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	Dedicated	Snap Fitting	1
	Rear Shimano Alivio SL-M430 9 speed	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	Dedicated	Snap Fitting	1
	Cable guide T12 101 175 2in1	Outer Casing OT-40SP	Dedicated	Snap Fitting	1
	ϕ 41 mm Bottom Bracket Shell	Cartridge Shimano BB-UN26	Dedicated	Threaded Fastening	1
	Cartridge Shimano BB-UN26	Lockring Shimano BB-UN26	Dedicated	Threaded Fastening	1
	Cartridge Shimano BB-UN26	Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	Dedicated	Non-Joining Assembling	1
	Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	Left Arm Shimano Acera FC-M391 170mm, 42x32x22T	Dedicated	Non-Joining Assembling	1
	Left Arm Shimano Acera FC-M391 170mm, 42x32x22T	Crank Cup Shimano Acera FC-M391 170mm, 42x32x22T	Dedicated	Threaded Fastening	1
	406 mm Seat Tube 35x2.05Tx1.6T 460L	Shimano Alivio FD-M430	Dedicated	Threaded Fastening	1
	Shimano Alivio FD-M430	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	End Frame INS RE 2012 001 Right	Shimano Deore RD-M592SGS	Dedicated	Threaded Fastening	1
	Shimano Deore RD-M592SGS	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	Araya DM 650 27.5"	32H ϕ10 mm l=145	Dedicated	Non-Joining	1

Product	Assembled Components		Assembly	Joining	Assembly
		mm Skewer		Assembling	
	End Frame INS RE 2012 001 Right	32H ϕ10 mm l=145 mm Skewer	Dedicated	Non-Joining Assembling	1
	32H ϕ10 mm l=145 mm Skewer	32H Rear Spring	Dedicated	Non-Joining Assembling	1
	32H ϕ10 mm l=145 mm Skewer	32H ϕ10 mm Nut	Dedicated	Threaded Fastening	1
	Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	KMC X-9 PGY 1/2x11/128x110 Links Super Light	Dedicated	Non-Joining Assembling	1
	Shimano FH-RM35 BZBL	Shimano CS-HG20, 11-34T 9 Speed	Dedicated	Threaded Fastening	1
	Shimano CS-HG20, 11-34T 9 Speed	KMC X-9 PGY 1/2x11/128x110 Links Super Light	Dedicated	Non-Joining Assembling	1
Cozmix CX2.0 27.5 size 16	669 mm Down Tube INS DT 2011 01	Decal Polygon M Cozmix 2.0 27.5”	Dedicated	Adhesive Bonding	1
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Decal Steering Entity Xpert	Dedicated	Adhesive Bonding	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Front Shimano Deore SL-M610 3 speed	Dedicated	Threaded Fastening	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Rear Shimano Deore SL-M610 10 speed	Dedicated	Threaded Fastening	1
	Front Shimano Deore SL-M610 3 speed	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	Dedicated	Snap Fitting	1
	Rear Shimano Deore SL-M610 10 speed	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	Dedicated	Snap Fitting	1
	Cable guide T12 101 175 2in1	Outer Casing OT-40SP	Dedicated	Snap Fitting	1
	ϕ 41 mm Bottom Bracket Shell	Right Cup and Bearing Shimano Hollowtech 2	Dedicated	Threaded Fastening	1
	Right Cup and Bearing Shimano Hollowtech 2	Left Cup Shimano Hollowtech 2	Dedicated	Threaded Fastening	1
	Right Cup and Bearing Shimano Hollowtech 2	Right Arm with Spindle Shimano Deore FC-M610	Dedicated	Non-Joining Assembling	1
	Right Arm with Spindle Shimano Deore FC-M610	Left Arm Shimano Deore FC-M610	Dedicated	Non-Joining Assembling	1
	Left Arm Shimano Deore FC-M610	Crank Cup Shimano Deore FC-M610	Dedicated	Threaded Fastening	1
	406 mm Seat Tube 35x2.05Tx1.6T 460L	Shimano Deore FD-M610	Dedicated	Threaded Fastening	1

Product	Assembled Components		Assembly	Joining	Assembly
	Shimano Deore FD-M610	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	End Frame INS RE 2012 001 Right	Shimano Deore RD-M610SGS	Dedicated	Threaded Fastening	1
	Shimano Deore RD-M610SGS	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	Araya DM 650 27.5"	32H ϕ10 mm l=145 mm Skewer	Dedicated	Non-Joining Assembling	1
	End Frame INS RE 2012 001 Right	32H ϕ10 mm l=145 mm Skewer	Dedicated	Non-Joining Assembling	1
	32H ϕ10 mm l=145 mm Skewer	32H Rear Spring	Dedicated	Non-Joining Assembling	1
	32H ϕ10 mm l=145 mm Skewer	32H ϕ10 mm Nut	Dedicated	Threaded Fastening	1
	Right Arm with Spindle Shimano Deore FC-M610	Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116 links	Dedicated	Non-Joining Assembling	1
	Shimano FH-RM35 BZBL	Shimano Deore CS-HG62, 11-36T, 10 Speed	Dedicated	Threaded Fastening	1
	Shimano Deore CS-HG62, 11-36T, 10 Speed	Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116 links	Dedicated	Non-Joining Assembling	1
Cozmix CX1.0 27.5 size 18	690 mm Down Tube INS DT 2011 01	Decal Polygon M Cozmix 1.0 27.5”	Dedicated	Adhesive Bonding	1
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Decal Steering Entity Xpert	Dedicated	Adhesive Bonding	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Front Shimano Alivio SL-M430 3 speed	Dedicated	Threaded Fastening	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Rear Shimano Alivio SL-M430 9 speed	Dedicated	Threaded Fastening	1
	Front Shimano Alivio SL-M430 3 speed	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	Dedicated	Snap Fitting	1
	Rear Shimano Alivio SL-M430 9 speed	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	Dedicated	Snap Fitting	1
	Cable guide T12 101 175 2in1	Outer Casing OT-40SP	Dedicated	Snap Fitting	1
	ϕ 41 mm Bottom Bracket Shell	Cartridge Shimano BB-UN26	Dedicated	Threaded Fastening	1
	Cartridge Shimano BB-UN26	Lockring Shimano BB-UN26	Dedicated	Threaded Fastening	1
	Cartridge Shimano BB-UN26	Right Arm with Spindle Shimano	Dedicated	Non-Joining Assembling	1

Product	Assembled Components		Assembly	Joining	Assembly
		Acera FC-M391 170mm, 42x32x22T			
	Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	Left Arm Shimano Acera FC-M391 170mm, 42x32x22T	Dedicated	Non-Joining Assembling	1
	Left Arm Shimano Acera FC-M391 170mm, 42x32x22T	Crank Cup Shimano Acera FC-M391 170mm, 42x32x22T	Dedicated	Threaded Fastening	1
	457 mm Seat Tube 35x2.05Tx1.6T 460L	Shimano Alivio FD-M430	Dedicated	Threaded Fastening	1
	Shimano Alivio FD-M430	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	End Frame INS RE 2012 001 Right	Shimano Deore RD-M592SGS	Dedicated	Threaded Fastening	1
	Shimano Deore RD-M592SGS	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	Araya DM 650 27.5"	32H ϕ10 mm l=145 mm Skewer	Dedicated	Non-Joining Assembling	1
	End Frame INS RE 2012 001 Right	32H ϕ10 mm l=145 mm Skewer	Dedicated	Non-Joining Assembling	1
	32H ϕ10 mm l=145 mm Skewer	32H Rear Spring	Dedicated	Non-Joining Assembling	1
	32H ϕ10 mm l=145 mm Skewer	32H ϕ10 mm Nut	Dedicated	Threaded Fastening	1
	Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	KMC X-9 PGY 1/2x11/128x110 Links Super Light	Dedicated	Non-Joining Assembling	1
	Shimano FH-RM35 BZBL	Shimano CS-HG20, 11-34T 9 Speed	Dedicated	Threaded Fastening	1
	Shimano CS-HG20, 11-34T 9 Speed	KMC X-9 PGY 1/2x11/128x110 Links Super Light	Dedicated	Non-Joining Assembling	1
Cozmix CX2.0 27.5 size 18	690 mm Down Tube INS DT 2011 01	Decal Polygon M Cozmix 2.0 27.5”	Dedicated	Adhesive Bonding	1
	SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Decal Steering Entity Xpert	Dedicated	Adhesive Bonding	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Front Shimano Deore SL-M610 3 speed	Dedicated	Threaded Fastening	1
	Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Rear Shimano Deore SL-M610 10 speed	Dedicated	Threaded Fastening	1
	Front Shimano Deore SL-M610 3 speed	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	Cable Protector VLZ 034 4mm	Outer Casing OT-40SP	Dedicated	Snap Fitting	1
	Rear Shimano Deore SL-M610 10 speed	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	Cable Protector VLZ	Outer Casing OT-	Dedicated	Snap Fitting	1

Product	Assembled Components		Assembly	Joining	Assembly
	034 4mm	40SP			
	Cable guide T12 101 175 2in1	Outer Casing OT-40SP	Dedicated	Snap Fitting	1
	ϕ 41 mm Bottom Bracket Shell	Right Cup and Bearing Shimano Hollowtech 2	Dedicated	Threaded Fastening	1
	Right Cup and Bearing Shimano Hollowtech 2	Left Cup Shimano Hollowtech 2	Dedicated	Threaded Fastening	1
	Right Cup and Bearing Shimano Hollowtech 2	Right Arm with Spindle Shimano Deore FC-M610	Dedicated	Non-Joining Assembling	1
	Right Arm with Spindle Shimano Deore FC-M610	Left Arm Shimano Deore FC-M610	Dedicated	Non-Joining Assembling	1
	Left Arm Shimano Deore FC-M610	Crank Cup Shimano Deore FC-M610	Dedicated	Threaded Fastening	1
	457 mm Seat Tube 35x2.05Tx1.6T 460L	Shimano Deore FD-M610	Dedicated	Threaded Fastening	1
	Shimano Deore FD-M610	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	End Frame INS RE 2012 001 Right	Shimano Deore RD-M610SGS	Dedicated	Threaded Fastening	1
	Shimano Deore RD-M610SGS	Outer Casing OT-40SP	Dedicated	Threaded Fastening	1
	Araya DM 650 27.5"	32H ϕ10 mm l=145 mm Skewer	Dedicated	Non-Joining Assembling	1
	End Frame INS RE 2012 001 Right	32H ϕ10 mm l=145 mm Skewer	Dedicated	Non-Joining Assembling	1
	32H ϕ10 mm l=145 mm Skewer	32H Rear Spring	Dedicated	Non-Joining Assembling	1
	32H ϕ10 mm l=145 mm Skewer	32H ϕ10 mm Nut	Dedicated	Threaded Fastening	1
	Right Arm with Spindle Shimano Deore FC-M610	Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116 links	Dedicated	Non-Joining Assembling	1
	Shimano FH-RM35 BZBL	Shimano Deore CS-HG62, 11-36T, 10 Speed	Dedicated	Threaded Fastening	1
	Shimano Deore CS-HG62, 11-36T, 10 Speed	Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116 links	Dedicated	Non-Joining Assembling	1

Appendix A11. Quantity of Recovered Sub Module for All Product Variant of 27.5” Hard Tail Cross Country Sport MTB Family

Sub Module	Component Type	Reused Quantity	Reconditioned Quantity	Repaired Quantity	Replaced Quantity
32H Front Axle Skewer	Sub Assembly	49,140	546	0	0
32H Rear Axle Skewer	Sub Assembly	49,140	546	0	0
ALX Alloy Cross Country size 16	Sub Assembly	24,570	273	270	4,887
ALX Alloy Cross Country size 18	Sub Assembly	24,570	273	270	4,887
Araya DM 650 27.5”	Part	106,920	1,188	0	0
Bottle Bolt TL 230B M5x12	Part	213,840	2,376	0	0
Bottle Cage	Part	53,460	594	0	0
Bracket 37-015B-290 M6	Part	53,460	594	0	0
Cable Protector VLZ 034 4mm	Part	0	0	0	0
Decal Polygon M Cozmix 1.0 27.5”	Part	35,640	396	0	0
Decal Polygon M Cozmix 2.0 27.5”	Part	17,820	198	0	0
Decal Steering Entity Xpert	Part	53,460	594	0	0
Entity Flux Saddle Steel Rail Velo Flux B XC	Sub Assembly	53,460	594	0	0
Entity Internal Sealed Bearing Head Set Strummer 1SI110 Caged ϕ28.6	Sub Assembly	49,140	546	0	0
Entity Xpert Alloy 30.9x350mm Kalloy SP712N	Part	53,460	594	0	0
Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Part	53,460	594	0	0
Entity Xpert Alloy 90mm CHUN-E IRS-06 ϕ28.6	Part	53,460	594	0	0
Front Shimano Alivio SL-M430 3 speed	Part	35,640	396	0	0
Front Shimano Deore SL-M610 3 speed	Part	17,820	198	0	0
Handle Grip VLG1312AD2L Lock	Part	0	0	0	0
KMC X-9 PGY 1/2x11/128x110 Links Super Light	Part	35,640	396	0	0
Outer Casing OT-40SP	Part	0	0	0	0
Promax 342Q 34.2QR	Part	106,920	1,188	0	0
Rear Shimano Alivio SL-M430 9 speed	Part	35,640	396	0	0
Rear Shimano Deore SL-M610 10 speed	Part	17,820	198	0	0
Rim Tape Nylon Red	Part	0	0	0	0

Sub Module	Component Type	Reused Quantity	Reconditioned Quantity	Repaired Quantity	Replaced Quantity
650B x 20mm					
Schwalbe Smart Sam 27.5”x2.10”	Part	0	0	0	0
Schwalbe SV 19	Part	0	0	0	0
Shimano Acera BL-M395	Part	106,920	1,188	0	0
Shimano Acera BR-M395 Front Left Brake Set	Sub Assembly	49,140	546	0	0
Shimano Acera BR-M395 Rear Right Brake Set	Sub Assembly	49,140	546	0	0
Shimano Acera FC-M391 170mm, 42x32x22T	Sub Assembly	32,760	364	0	0
Shimano Alivio FD-M430	Part	35,640	396	0	0
Shimano BB-UN26	Sub Assembly	32,760	364	0	0
Shimano CS-HG20, 11-34T 9 Speed	Part	35,640	396	0	0
Shimano Deore CN-HG54 1/2" x 11/128", Closing link: Chain Pin, 116 links	Part	17,820	198	0	0
Shimano Deore CS-HG62, 11-36T 10 Speed	Part	17,820	198	0	0
Shimano Deore FC-M610, 170mm, 42x32x24T	Sub Assembly	16,380	182	0	0
Shimano Deore FD-M610	Part	17,820	198	0	0
Shimano Deore RD-M592SGS	Part	35,640	396	0	0
Shimano Deore RD-M610SGS	Part	17,820	198	0	0
Shimano FH-RM35 Front Hub	Part	53,460	594	0	0
Shimano FH-RM35 Rear Free Hub	Part	53,460	594	0	0
Shimano Hollowtech 2	Sub Assembly	16,380	182	0	0
Shimano SM-RT30 160 mm	Part	106,920	1,188	0	0
Side Kick Stand	Part	53,460	594	0	0
Spoke 14G x 270 mm BK	Sub Assembly	1,572,480	17,472	0	0
Spoke 14G x 272 mm BK	Sub Assembly	1,572,480	17,472	0	0
SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Part	53,460	594	0	0
Sticker Insera Sena 5x4 cm	Part	0	0	0	0
Sticker SNI Poly M Cozmic CX 27.5	Part	0	0	0	0
VP Component VP-199	Part	106,920	1,188	0	0

Appendix A12. Quantity of Recovered Component for All Product Variant of 27.5” Hard Tail Cross Country Sport MTB Family

Component	Recovered Quantity
Cable Protector VLZ 034 4mm	0
100 mm Head Tube INS HT 2011 01	60,000
406 mm Seat Tube 35x2.05Tx1.6T 460L	30,000
424 mm Seat Stay INS SS 2011	60,000
425 mm Chain Stay INS CS 2011	120,000
547 mm Top Tube INS TT 2011	30,000
669 mm Down Tube INS DT 2011 01	30,000
Boss Nut VERTECH 46 041B 090	240,000
Cable guide C11 101 095 Alloy	420,000
Cable guide T12 101 175 2in1	180,000
Cable Stopper ALY JS AL3 1P	60,000
End Frame INS RE 2012 001 Left	60,000
End Frame INS RE 2012 001 Right	60,000
ϕ 41 mm Bottom Bracket Shell	60,000
Seat Stay Bracket INS BR 2011	60,000
457 mm Seat Tube 35x2.05Tx1.6T 460L	30,000
512 mm Seat Stay INS SS 2011	60,000
561 mm Top Tube INS TT 2011	30,000
690 mm Down Tube INS DT 2011 01	30,000
Shimano Acera BL-M395	108,108
Bracket Shimano Acera BR-M395	99,372
Caliper Shimano Acera BR-M395	99,372
Front Brake Lever Shimano Acera BR-M395	49,686
Hose Shimano Acera BR-M395	99,372
Rear Brake Lever Shimano Acera BR-M395	49,686
Shimano SM-RT30 160 mm	108,108
Araya DM 650 27.5"	108,108
32H ϕ9 mm l=108 mm Skewer	49,686
32H ϕ9 mm Nut	49,686
32H Front Spring	99,372
Shimano FH-RM35 BL	54,054
Rim Tape Nylon Red 650B x 20mm	0
Eyelet 14G x 270	1,589,952
Nipple 14G x 270	1,589,952
Spoke 14G x 270	1,589,952
Schwalbe SV 19	0
Schwalbe Smart Sam 27.5”x2.10”	0
32H ϕ10 mm Nut	49,686
32H ϕ10 mm l=145 mm Skewer	49,686
32H Rear Spring	99,372
Shimano FH-RM35 BZBL	54,054
Eyelet 14G x 272	1,589,952
Nipple 14G x 272	1,589,952
Spoke 14G x 272	1,589,952
Promax 342Q 34.2QR	108,108
Saddle Steel Rail Velo Flux B XC	54,054
Saddle	54,054
Entity Xpert Alloy 30.9x350mm Kalloy SP712N	54,054
SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	54,054
Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	54,054
Handle Grip VLG1312AD2L Lock	0
Bearing 1SI110	99,372
Stem Cap SP 23 BK ϕ28.6	49,686

Component	Recovered Quantity
Washer 1SI110 28.6x33x10 mm	99,372
Washer 1SI110 28.6x33x5 mm	99,372
Entity Expert Alloy 90mm CHUN-E IRS-06 ϕ28.6	54,054
Sticker SNI Poly M Cozmic CX 27.5	0
Sticker Insera Sena 5x4 cm	0
Bracket 37-015B-290 M6	54,054
Side Kick Stand	54,054
Bottle Cage	54,054
Bottle Bolt TL 230B M5x12	216,216
Shimano Alivio FD-M430	36,036
Front Shimano Alivio SL-M430 3 speed	36,036
Rear Shimano Alivio SL-M430 9 speed	36,036
Outer Casing OT-40SP	0
Shimano Deore RD-M592SGS	36,036
Crank Cup Shimano Acera FC-M391 170mm, 42x32x22T	33,124
Left Arm Shimano Acera FC-M391 170mm, 42x32x22T	33,124
Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	33,124
Cartridge Shimano BB-UN26	33,124
Lockring Shimano BB-UN26	33,124
VP Component VP-199	108,108
Shimano CS-HG20, 11-34T 9 Speed	36,036
KMC X-9 PGY 1/2x11/128x110 Links Super Light	36,036
Decal Steering Entity Xpert	54,054
Decal Polygon M Cozmix 1.0 27.5”	36,036
Shimano Deore FD-M610	18,018
Shimano Deore SL-M610 3 speed	18,018
Shimano Deore SL-M610 10 speed	18,018
Shimano Deore RD-M610SGS	18,018
Crank Cup Shimano Deore FC-M610	16,562
Left Arm Shimano Deore FC-M610	16,562
Right Arm with Spindle Shimano Deore FC-M610	16,562
Left Cup Shimano Hollowtech 2	16,562
Right Cup and Bearing Shimano Hollowtech 2	16,562
Shimano Deore CS-HG62, 11-36T, 10 Speed	18,018
Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116 links	18,018
Decal Polygon M Cozmix 2.0 27.5”	18,018

Appendix A13. Quantity of Unrecovered Component of All Product Variant of 27.5" Hard Tail Cross Country Sport MTB Family

Component	Material	Quantity	End of Life Strategy
100 mm Head Tube INS HT 2011 01	Aluminium Alloy	360	Recycled
32H ϕ10 mm l=145 mmSkewer	Alloy Steel	10314	Recycled
32H ϕ10 mm Nut	Alloy Steel	10314	Recycled
32H ϕ9 mm l=108 mm Skewer	Alloy Steel	10314	Recycled
32H ϕ9 mm Nut	Alloy Steel	10314	Recycled
32H Front Spring	Alloy Steel	20628	Recycled
32H Rear Spring	Alloy Steel	20628	Recycled
406 mm Seat Tube 35x2.05Tx1.6T 460L	Aluminium Alloy	180	Recycled
424 mm Seat Stay INS SS 2011	Aluminium Alloy	361	Recycled
425 mm Chain Stay INS CS 2011	Aluminium Alloy	722	Recycled
457 mm Seat Tube 35x2.05Tx1.6T 460L	Aluminium Alloy	180	Recycled
512 mm Seat Stay INS SS 2011	Aluminium Alloy	361	Recycled
547 mm Top Tube INS TT 2011	Aluminium Alloy	180	Recycled
561 mm Top Tube INS TT 2011	Aluminium Alloy	180	Recycled
669 mm Down Tube INS DT 2011 01	Aluminium Alloy	180	Recycled
690 mm Down Tube INS DT 2011 01	Aluminium Alloy	180	Recycled
Araya DM 650 27.5"	Alloy Steel	11,892	Recycled
Bearing 1SI110	Alloy Steel	20628	Recycled
Boss Nut VERTECH 46 041B 090	Aluminium Alloy	1444	Recycled
Bottle Bolt TL 230B M5x12	Aluminium Alloy	23784	Recycled
Bottle Cage	Aluminium Alloy	5946	Recycled
Bracket 37-015B-290 M6	Alloy Steel	5946	Recycled
Bracket Shimano Acera BR-M395	Aluminium Alloy	20628	Recycled
Cable guide C11 101 095 Alloy	Aluminium Alloy	2528	Recycled
Cable guide T12 101 175 2in1	Aluminium Alloy	1082	Recycled
Cable Protector VLZ 034 4mm	Thermoset	60000	Incinerated
Cable Stopper ALY JS AL3 1P	Aluminium Alloy	360	Recycled
Caliper Shimano Acera BR-M395	Aluminium Alloy	20628	Recycled
Cartridge Shimano BB-UN26	Alloy Steel	6876	Recycled
Crank Cup Shimano Acera FC-M391 170mm, 42x32x22T	Alloy Steel	6876	Recycled
Crank Cup Shimano Deore FC-M610	Alloy Steel	3438	Recycled
Decal Polygon M Cozmix 1.0 27.5"	Thermoplastics	3964	Recycled
Decal Polygon M Cozmix 2.0 27.5"	Thermoplastics	1982	Recycled
Decal Steering Entity Xpert	Thermoplastics	5964	Recycled
End Frame INS RE 2012 001 Left	Aluminium Alloy	360	Recycled
End Frame INS RE 2012 001 Right	Aluminium Alloy	360	Recycled
Entity Expert Alloy 90mm CHUN-E IRS-06 ϕ28.6	Alloy Steel	5946	Recycled
Entity Xpert Alloy 30.9x350mm Kalloy SP712N	Aluminium Alloy	5946	Recycled
Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	Alloy Steel	5946	Recycled
Eyelet 14G x 270	Aluminium Alloy	330048	Recycled
Eyelet 14G x 272	Aluminium Alloy	330048	Recycled
ϕ 41 mm Bottom Bracket Shell	Aluminium Alloy	360	Recycled
Front Brake Lever Shimano Acera BR-M395	Aluminium Alloy	10314	Recycled
Front Shimano Alivio SL-M430 3 speed	Mixed Material	3964	Landfilled
Handle Grip VLG1312AD2L Lock	Thermoset	120000	Incinerated
Hose Shimano Acera BR-M395	Thermoset	20628	Incinerated
KMC X-9 PGY 1/2x11/128x110 Links Super Light	Alloy Steel	3964	Recycled
Left Arm Shimano Acera FC-M391	Alloy Steel	6876	Recycled

Component	Material	Quantity	End of Life Strategy
170mm, 42x32x22T			
Left Arm Shimano Deore FC-M610	Alloy Steel	3438	Recycled
Left Cup Shimano Hollowtech 2	Alloy Steel	3438	Recycled
Lockring Shimano BB-UN26	Alloy Steel	6876	Recycled
Nipple 14G x 270	Aluminium Alloy	330048	Recycled
Nipple 14G x 272	Aluminium Alloy	330048	Recycled
Outer Casing OT-40SP	Thermoset	120000	Incinerated
Promax 342Q 34.2QR	Aluminium Alloy	11892	Recycled
Rear Brake Lever Shimano Acera BR-M395	Aluminium Alloy	10314	Recycled
Rear Shimano Alivio SL-M430 9 speed	Mixed Material	3964	Landfilled
Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	Alloy Steel	6876	Recycled
Right Arm with Spindle Shimano Deore FC-M610	Alloy Steel	3438	Recycled
Right Cup and Bearing Shimano Hollowtech 2	Alloy Steel	3438	Recycled
Rim Tape Nylon Red 650B x 20mm	Thermoset	120000	Incinerated
Saddle	Thermoset	5946	Incinerated
Saddle Steel Rail Velo Flux B XC	Alloy Steel	5946	Recycled
Schwalbe Smart Sam 27.5”x2.10”	Thermoset	120000	Incinerated
Schwalbe SV 19	Thermoset	120000	Incinerated
Seat Stay Bracket INS BR 2011	Aluminium Alloy	360	Recycled
Shimano Acera BL-M395	Aluminium Alloy	11892	Recycled
Shimano Alivio FD-M430	Carbon Steel	3964	Recycled
Shimano CS-HG20, 11-34T 9 Speed	Carbon Steel	3964	Recycled
Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116 links	Alloy Steel	1982	Recycled
Shimano Deore CS-HG62, 11-36T, 10 Speed	Carbon Steel	1982	Recycled
Shimano Deore FD-M610	Carbon Steel	1982	Recycled
Shimano Deore RD-M592SGS	Carbon Steel	3964	Recycled
Shimano Deore RD-M610SGS	Carbon Steel	1982	Recycled
Shimano Deore SL-M610 10 speed	Mixed Material	1982	Landfilled
Shimano Deore SL-M610 3 speed	Mixed Material	1982	Landfilled
Shimano FH-RM35 BL	Alloy Steel	5946	Recycled
Shimano FH-RM35 BZBL	Alloy Steel	5946	Recycled
Shimano SM-RT30 160 mm	Stainless Steel	11892	Recycled
Side Kick Stand	Alloy Steel	5946	Recycled
Spoke 14G x 270	Alloy Steel	330048	Recycled
Spoke 14G x 272	Alloy Steel	330048	Recycled
SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	Aluminium Alloy	5946	Recycled
Stem Cap SP 23 BK ϕ28.6	Aluminium Alloy	10314	Recycled
Sticker Insera Sena 5x4 cm	Thermoset	60000	Incinerated
Sticker SNI Poly M Cozmic CX 27.5	Thermoset	60000	Incinerated
VP Component VP-199	Aluminium Alloy	11892	Recycled
Washer 1SI110 28.6x33x10 mm	Aluminium Alloy	20628	Recycled
Washer 1SI110 28.6x33x5 mm	Aluminium Alloy	20628	Recycled

Appendix A14. Weight of Recovered Material for All Product Variant of 27.5” Hard Tail Cross Country Sport MTB Family

Recovered Material	Raw Material Shape	End of Life Strategy	Weight (gram)
Alloy Steel	Bulk	Recycled	49,090,754
Aluminium Alloy	Bulk	Recycled	30,176,521
Carbon Steel	Bulk	Recycled	5,714,106
Mixed Material	Bulk	Landfilled	3,646,880
Stainless Steel	Bulk	Recycled	2,164,344
Thermoplastics	Bulk	Recycled	26,784
Thermoset	Bulk	Incinerated	138,625,536

Appendix A15. Viable Primary and Secondary Manufacturing Processes for In-house Component of 27.5” Hard Tail Cross Country Sport MTB Family

In-house Component	Production Volume	Material Shape	Viable Primary and Secondary Process
100 mm Head Tube INS HT 2011 01	60,000	Bulk	Gravity Mould Casting
		Bulk	Investment Casting
		Bulk	Lost Foam Casting
		Bulk	Sand Casting
		Bulk	Shell Moulding
		Round Tubes	Closed Die Forging
		Round Tubes	Counterboring
		Round Tubes	Countersinking
		Round Tubes	Drilling
		Round Tubes	Electromagnetic Forming
425 mm Chain Stay INS CS 2011	120,000	Bulk	Gravity Mould Casting
		Bulk	Investment Casting
		Bulk	Lost Foam Casting
		Bulk	Sand Casting
		Bulk	Shell Moulding
		Bulk	Slush Casting
		Flat Bars	Closed Die Forging
		Square/ Rectangular Tubes	Closed Die Forging
ϕ 41 mm Bottom Bracket Shell	60,000	Bulk	Investment Casting
		Bulk	Lost Foam Casting
		Bulk	Sand Casting
		Bulk	Shell Moulding
		Round Tubes	Boring
		Round Tubes	Closed Die Forging
		Round Tubes	Roll Forming
		Sheets	Roll Bending
406 mm Seat Tube 35x2.05Tx1.6T 460L	30,000	Bulk	Gravity Mould Casting
		Bulk	Investment Casting
		Bulk	Lost Foam Casting
		Bulk	Sand Casting
		Bulk	Shell Moulding
		Round Tubes	Boring
		Round Tubes	Closed Die Forging
		Round Tubes	Roll Forming
		Sheets	Roll Bending
424 mm Seat Stay INS SS 2011	60,000	Bulk	Investment Casting
		Bulk	Lost Foam Casting
		Bulk	Sand Casting
		Bulk	Shell Moulding
		Round Tubes	Closed Die Forging
547 mm Top Tube INS TT 2011	30,000	Bulk	Gravity Mould Casting
		Bulk	Investment Casting
		Bulk	Lost Foam Casting
		Bulk	Sand Casting
		Bulk	Shell Moulding
		Square/ Rectangular Tubes	Closed Die Forging
669 mm Down Tube INS DT 2011 01	30,000	Bulk	Investment Casting
		Bulk	Lost Foam Casting
		Bulk	Sand Casting
		Bulk	Shell Moulding
		Square/ Rectangular Tubes	Closed Die Forging
457 mm Seat Tube	30,000	Bulk	Gravity Mould Casting

In-house Component	Production Volume	Material Shape	Viable Primary and Secondary Process
35x2.05Tx1.6T 460L		Bulk	Investment Casting
		Bulk	Lost Foam Casting
		Bulk	Sand Casting
		Bulk	Shell Moulding
		Round Tubes	Boring
		Round Tubes	Closed Die Forging
		Round Tubes	Roll Forming
		Sheets	Roll Bending
512 mm Seat Stay INS SS 2011	60,000	Bulk	Investment Casting
		Bulk	Lost Foam Casting
		Bulk	Sand Casting
		Bulk	Shell Moulding
		Round Tubes	Closed Die Forging
561 mm Top Tube INS TT 2011	30,000	Bulk	Gravity Mould Casting
		Bulk	Investment Casting
		Bulk	Lost Foam Casting
		Bulk	Sand Casting
		Bulk	Shell Moulding
		Square/ Rectangular Tubes	Closed Die Forging
690 mm Down Tube INS DT 2011 01	30,000	Bulk	Investment Casting
		Bulk	Lost Foam Casting
		Bulk	Sand Casting
		Bulk	Shell Moulding
		Square/ Rectangular Tubes	Closed Die Forging

Appendix A16. Selected Manufacturing Process for In-house Component of 27.5” Hard Tail Cross Country Sport MTB Family

In-house Component	Material Shape	Selected Process	Min Size Tolerance (mm)	Max Size Tolerance (mm)	Min Surface Roughness (μm)	Max Surface Roughness (μm)
100 mm Head Tube INS HT 2011 01	Round Tubes	Closed Die Forging	0.65	6	1.6	25
425 mm Chain Stay INS CS 2011	Square/ Rectangular Tubes	Closed Die Forging	0.65	6	1.6	25
ϕ 41 mm Bottom Bracket Shell	Round Tubes	Closed Die Forging	0.65	6	1.6	25
406 mm Seat Tube 35x2.05Tx1.6T 460L	Round Tubes	Closed Die Forging	0.65	6	1.6	25
424 mm Seat Stay INS SS 2011	Round Tubes	Closed Die Forging	0.65	6	1.6	25
547 mm Top Tube INS TT 2011	Square/ Rectangular Tubes	Closed Die Forging	0.65	6	1.6	25
669 mm Down Tube INS DT 2011 01	Square/ Rectangular Tubes	Closed Die Forging	0.65	6	1.6	25
457 mm Seat Tube 35x2.05Tx1.6T 460L	Round Tubes	Closed Die Forging	0.65	6	1.6	25
512 mm Seat Stay INS SS 2011	Round Tubes	Closed Die Forging	0.65	6	1.6	25
561 mm Top Tube INS TT 2011	Square/ Rectangular Tubes	Closed Die Forging	0.65	6	1.6	25
690 mm Down Tube INS DT 2011 01	Square/ Rectangular Tubes	Closed Die Forging	0.65	6	1.6	25

Appendix A17. Viable and Selected Cutting Process for In-house Component of 27.5" Hard Tail Cross Country Sport MTB Family

In-house Component	Viable Process	Selected Process
100 mm Head Tube INS HT 2011 01	Cutting Off	Sawing
	Friction Sawing	
	Laser Beam Cutting	
	Plasma Cutting	
	Sawing	
425 mm Chain Stay INS CS 2011	Cutting Off	Sawing
	Friction Sawing	
	Laser Beam Cutting	
	Plasma Cutting	
	Sawing	
ϕ 41 mm Bottom Bracket Shell	Cutting Off	Sawing
	Friction Sawing	
	Laser Beam Cutting	
	Plasma Cutting	
	Sawing	
406 mm Seat Tube 35x2.05Tx1.6T 460L	Cutting Off	Sawing
	Friction Sawing	
	Laser Beam Cutting	
	Plasma Cutting	
	Sawing	
424 mm Seat Stay INS SS 2011	Cutting Off	Sawing
	Friction Sawing	
	Laser Beam Cutting	
	Plasma Cutting	
	Sawing	
547 mm Top Tube INS TT 2011	Cutting Off	Sawing
	Friction Sawing	
	Laser Beam Cutting	
	Plasma Cutting	
	Sawing	
669 mm Down Tube INS DT 2011 01	Cutting Off	Sawing
	Friction Sawing	
	Laser Beam Cutting	
	Plasma Cutting	
	Sawing	
457 mm Seat Tube 35x2.05Tx1.6T 460L	Cutting Off	Sawing
	Friction Sawing	
	Laser Beam Cutting	
	Plasma Cutting	
	Sawing	
512 mm Seat Stay INS SS 2011	Cutting Off	Sawing
	Friction Sawing	
	Laser Beam Cutting	
	Plasma Cutting	
	Sawing	
561 mm Top Tube INS TT 2011	Cutting Off	Sawing
	Friction Sawing	
	Laser Beam Cutting	
	Plasma Cutting	
	Sawing	
690 mm Down Tube INS DT 2011 01	Cutting Off	Sawing
	Friction Sawing	
	Laser Beam Cutting	

In-house Component	Viable Process	Selected Process
	Plasma Cutting	
	Sawing	

Appendix A18. Viable Primary and Secondary Manufacturing Processes for Additional Feature of In-house Component of 27.5” Hard Tail Cross Country Sport MTB Family

In-house Component	Additional Feature Name	Additional Feature Type	Viable Primary and Secondary Process
406 mm Seat Tube 35x2.05Tx1.6T 460L	Seat Tube Hole 1	Subtractive: Radial Holes	Chem. / Photochemical Machining
			Drilling
			Nibbling
			Notching
			Perforating
669 mm Down Tube INS DT 2011 01	Down Tube Hole 1	Subtractive: Radial Holes	Chem. / Photochemical Machining
			Drilling
			Nibbling
			Notching
			Perforating
457 mm Seat Tube 35x2.05Tx1.6T 460L	Seat Tube Hole 1	Subtractive: Radial Holes	Chem. / Photochemical Machining
			Drilling
			Nibbling
			Notching
			Perforating
690 mm Down Tube INS DT 2011 01	Down Tube Hole 1	Subtractive: Radial Holes	Chem. / Photochemical Machining
			Drilling
			Nibbling
			Notching
			Perforating

Appendix A19. Selected Manufacturing Process for Additional Feature of In-house Component of 27.5” Hard Tail Cross Country Sport MTB Family

In-house Component	**Selected Process**	**Min Size Tolerance (mm)**	**Max Size Tolerance (mm)**	**Min Surface Roughness (μm)**	**Max Surface Roughness (μm)**
406 mm Seat Tube 35x2.05Tx1.6T 460L	Drilling	0.015	0.5	0.4	12.5
669 mm Down Tube INS DT 2011 01	Drilling	0.015	0.5	0.4	12.5
457 mm Seat Tube 35x2.05Tx1.6T 460L	Drilling	0.015	0.5	0.4	12.5
690 mm Down Tube INS DT 2011 01	Drilling	0.015	0.5	0.4	12.5

Appendix A20. Viable Tertiary Manufacturing Processes to Achieve the Required Size Tolerance for In-house Component of 27.5” Hard Tail Cross Country Sport MTB Family

In-house Component	Required Size Tolerance	Viable Tertiary Process to Achieve the Size Tolerance	Selected Process	Achieved Size Tolerance
100 mm Head Tube INS HT 2011 01	0.2	Centre Type Grinding In / End Feed Centreless Grinding	Centre Type Grinding	0.00065
ϕ41 mm Bottom Bracket Shell	0.2	Centre Type Grinding Through Feed Centreless Grinding In / End Feed Centreless Grinding	Centre Type Grinding	0.00065
406 mm Seat Tube 35x2.05Tx1.6T 460L	0.05	Centre Type Grinding Through Feed Centreless Grinding In / End Feed Centreless Grinding	Centre Type Grinding	0.00065
547 mm Top Tube INS TT 2011	0.05	Surface Grinding	Surface Grinding	0.0015
457 mm Seat Tube 35x2.05Tx1.6T 460L	0.05	Centre Type Grinding Through Feed Centreless Grinding In / End Feed Centreless Grinding	Centre Type Grinding	0.00065
561 mm Top Tube INS TT 2011	0.05	Surface Grinding	Surface Grinding	0.0015

Appendix A21. Viable and Selected Surface Finishing Process for In-house Component of 27.5” Hard Tail Cross Country Sport MTB Family

In-house Component	Required Surface Finish	Viable Process	Selected Process	Basic Surface Finish
100 mm Head Tube INS HT 2011 01	Organic Finished	Painting – Brushing Painting – Dipping Painting – Electrodeposition Painting - Powder Coating Painting – Spray	Painting – Spray	Yes
425 mm Chain Stay INS CS 2011	Organic Finished	Painting – Brushing Painting – Dipping Painting - Powder Coating Painting – Spray	Painting – Spray	Yes
ϕ 41 mm Bottom Bracket Shell	Organic Finished	Painting – Brushing Painting – Dipping Painting – Electrodeposition Painting - Powder Coating Painting – Spray	Painting – Spray	Yes
406 mm Seat Tube 35x2.05Tx1.6T 460L	Organic Finished	Painting – Brushing Painting – Dipping Painting – Electrodeposition Painting - Powder Coating Painting – Spray	Painting – Spray	Yes
424 mm Seat Stay INS SS 2011	Organic Finished	Painting – Brushing Painting – Dipping Painting - Powder Coating Painting – Spray	Painting – Spray	Yes
547 mm Top Tube INS TT 2011	Organic Finished	Painting – Brushing Painting – Dipping Painting - Powder Coating Painting – Spray	Painting – Spray	Yes
669 mm Down Tube INS DT 2011 01	Organic Finished	Painting – Brushing Painting – Dipping Painting - Powder Coating Painting – Spray	Painting – Spray	Yes
457 mm Seat Tube 35x2.05Tx1.6T 460L	Organic Finished	Painting – Brushing Painting – Dipping Painting – Electrodeposition Painting - Powder Coating Painting – Spray	Painting – Spray	Yes
512 mm Seat Stay INS SS 2011	Organic Finished	Painting – Brushing Painting – Dipping Painting - Powder Coating Painting – Spray	Painting – Spray	Yes
561 mm Top Tube INS TT 2011	Organic Finished	Painting – Brushing Painting – Dipping Painting - Powder Coating Painting – Spray	Painting – Spray	Yes
690 mm Down Tube INS DT 2011 01	Organic Finished	Painting – Brushing Painting – Dipping Painting - Powder Coating	Painting – Spray	Yes

In-house Component	Required Surface Finish	Viable Process	Selected Process	Basic Surface Finish
		Painting – Spray		

Appendix A22. Viable Cleaning Process after Basic Surface Finish Process for In-house Component of 27.5” Hard Tail Cross Country Sport MTB Family

In-house Component	Prior Process	Post Process	Viable Cleaning Process	Selected Cleaning Process
100 mm Head Tube INS HT 2011 01	Polishing and Buffing	Painting – Spray	Emulsion Cleaning (Spray or Immersion) Alkaline Cleaning (Immersion and Spray)	Alkaline Cleaning (Immersion and Spray)
425 mm Chain Stay INS CS 2011	Polishing and Buffing	Painting – Spray	Emulsion Cleaning (Spray or Immersion) Alkaline Cleaning (Immersion and Spray)	Alkaline Cleaning (Immersion and Spray)
ϕ 41 mm Bottom Bracket Shell	Polishing and Buffing	Painting – Spray	Emulsion Cleaning (Spray or Immersion) Alkaline Cleaning (Immersion and Spray)	Alkaline Cleaning (Immersion and Spray)
406 mm Seat Tube 35x2.05Tx1.6T 460L	Polishing and Buffing	Painting – Spray	Emulsion Cleaning (Spray or Immersion) Alkaline Cleaning (Immersion and Spray)	Alkaline Cleaning (Immersion and Spray)
424 mm Seat Stay INS SS 2011	Polishing and Buffing	Painting – Spray	Emulsion Cleaning (Spray or Immersion) Alkaline Cleaning (Immersion and Spray)	Alkaline Cleaning (Immersion and Spray)
547 mm Top Tube INS TT 2011 669 mm Down Tube INS DT 2011 01	Polishing and Buffing	Painting – Spray	Emulsion Cleaning (Spray or Immersion) Alkaline Cleaning (Immersion and Spray)	Alkaline Cleaning (Immersion and Spray)
457 mm Seat Tube 35x2.05Tx1.6T 460L	Polishing and Buffing	Painting – Spray	Emulsion Cleaning (Spray or Immersion) Alkaline Cleaning (Immersion and Spray)	Alkaline Cleaning (Immersion and Spray)
512 mm Seat Stay INS SS 2011 561 mm Top Tube INS TT 2011	Polishing and Buffing	Painting – Spray	Emulsion Cleaning (Spray or Immersion) Alkaline Cleaning (Immersion and Spray)	Alkaline Cleaning (Immersion and Spray)
690 mm Down Tube INS DT 2011 01	Polishing and Buffing	Painting – Spray	Emulsion Cleaning (Spray or Immersion) Alkaline Cleaning (Immersion and	Alkaline Cleaning (Immersion and Spray)

In-house Component	Prior Process	Post Process	Viable Cleaning Process	Selected Cleaning Process
			Spray)	
425 mm Chain Stay INS CS 2011 ϕ 41 mm Bottom Bracket Shell	Polishing and Buffing	Painting – Spray	Emulsion Cleaning (Spray or Immersion)	Alkaline Cleaning (Immersion and Spray)
			Alkaline Cleaning (Immersion and Spray)	
406 mm Seat Tube 35x2.05Tx1.6T 460L	Polishing and Buffing	Painting – Spray	Emulsion Cleaning (Spray or Immersion)	Alkaline Cleaning (Immersion and Spray)
			Alkaline Cleaning (Immersion and Spray)	

Appendix A23. Manufacturing Process Chain for In-house Component

In-house Component	To form Main Shape	To Cut Raw Material	to Achieve Required Size Tolerance
100 mm Head Tube INS HT 2011 01	Closed Die Forging	Sawing	Centre Type Grinding
406 mm Seat Tube 35x2.05Tx1.6T 460L	Closed Die Forging	Sawing	Surface Grinding
424 mm Seat Stay INS SS 2011	Closed Die Forging	Sawing	N/A
425 mm Chain Stay INS CS 2011	Closed Die Forging	Sawing	N/A
547 mm Top Tube INS TT 2011	Closed Die Forging	Sawing	Surface Grinding
669 mm Down Tube INS DT 2011 01	Closed Die Forging	Sawing	N/A
ϕ 41 mm Bottom Bracket Shell	Closed Die Forging	Sawing	Centre Type Grinding
457 mm Seat Tube 35x2.05Tx1.6T 460L	Closed Die Forging	Sawing	Centre Type Grinding
512 mm Seat Stay INS SS 2011	Closed Die Forging	Sawing	N/A
561 mm Top Tube INS TT 2011	Closed Die Forging	Sawing	Surface Grinding
690 mm Down Tube INS DT 2011 01	Closed Die Forging	Sawing	N/A

to Achieve Required Surface Roughness	to Achieve Required Material Property	to Achieve Basic Surface Finish	to Achieve Required Basic Surface Finish
N/A	Solution Treating and Precipitation Hardening	Polishing and Buffing	Painting - Spray
N/A	Solution Treating and Precipitation Hardening	Polishing and Buffing	Painting - Spray
N/A	Solution Treating and Precipitation Hardening	Polishing and Buffing	Painting - Spray
N/A	Solution Treating and Precipitation Hardening	Polishing and Buffing	Painting - Spray
N/A	Solution Treating and Precipitation Hardening	Polishing and Buffing	Painting - Spray
N/A	Solution Treating and Precipitation Hardening	Polishing and Buffing	Painting - Spray
N/A	Solution Treating and Precipitation Hardening	Polishing and Buffing	Painting - Spray
N/A	Solution Treating and Precipitation Hardening	Polishing and Buffing	Painting - Spray
N/A	Solution Treating and Precipitation Hardening	Polishing and Buffing	Painting - Spray
N/A	Solution Treating and Precipitation Hardening	Polishing and Buffing	Painting - Spray
N/A	Solution Treating and Precipitation Hardening	Polishing and Buffing	Painting - Spray

1st Cleaning Process	2nd Cleaning Process
N/A	Alkaline Cleaning (Immersion and Spray)
N/A	Alkaline Cleaning (Immersion and Spray)
N/A	Alkaline Cleaning (Immersion and Spray)
N/A	Alkaline Cleaning (Immersion and Spray)
N/A	Alkaline Cleaning (Immersion and Spray)
N/A	Alkaline Cleaning (Immersion and Spray)
N/A	Alkaline Cleaning (Immersion and Spray)
N/A	Alkaline Cleaning (Immersion and Spray)
N/A	Alkaline Cleaning (Immersion and Spray)
N/A	Alkaline Cleaning (Immersion and Spray)
N/A	Alkaline Cleaning (Immersion and Spray)

Appendix A24. Manufacturing Process Chain for Additional Feature

In-house Component	Additional Feature Name	To Add Feature
406 mm Seat Tube 35x2.05Tx1.6T 460L	Seat Tube Hole 1	Drilling
457 mm Seat Tube 35x2.05Tx1.6T 460L	Seat Tube Hole 2	Drilling
669 mm Down Tube INS DT 2011 01	Down Tube Hole 1	Drilling
690 mm Down Tube INS DT 2011 01	Down Tube Hole 2	Drilling

Appendix A25. Purchased Quantity and Order Quantity of Outsourced Component for All Product Variant of 27.5” Hard Tail Cross Country Sport MTB Family

Component	Purchased Quantity	Supplier	Order Quantity
32H ϕ10 mm l=145 mm Skewer	70,314	Araya	8
32H ϕ10 mm Nut	70,314	Araya	8
32H ϕ9 mm l=108 mm Skewer	70,314	Araya	8
32H ϕ9 mm Nut	70,314	Araya	8
32H Front Spring	140,628	Araya	15
32H Rear Spring	140,628	Araya	15
Araya DM 650 27.5"	131,892	Araya	14
Bearing 1SI110	140,628	Garuda Enterprise	15
Boss Nut VERTECH 46 041B 090	240,000	Aneka Jaya Baut Sejahtera	24
Bottle Bolt TL 230B M5x12	263,784	Aneka Jaya Baut Sejahtera	27
Bottle Cage	65,946	Garuda Enterprise	7
Bracket 37-015B-290 M6	65,946	Cheng's Enterprise	7
Bracket Shimano Acera BR-M395	140,628	Shimano Singapore	15
Cable guide C11 101 095 Alloy	420,000	Ever Glory Machinery	42
Cable guide T12 101 175 2in1	180,000	Ever Glory Machinery	18
Cable Protector VLZ 034 4mm	240,000	Cheng's Enterprise	24
Cable Stopper ALY JS AL3 1P	60,000	Ever Glory Machinery	6
Caliper Shimano Acera BR-M395	140,628	Shimano Singapore	15
Cartridge Shimano BB-UN26	46,876	Shimano Singapore	5
Crank Cup Shimano Acera FC-M391 170mm, 42x32x22T	46,876	Shimano Singapore	5
Crank Cup Shimano Deore FC-M610	23,438	Shimano Singapore	3
Decal Polygon M Cozmix 1.0 27.5”	43,964	Oriole	5
Decal Polygon M Cozmix 2.0 27.5”	21,982	Oriole	3
Decal Steering Entity Xpert	65,946	Thunder Graphic	7
End Frame INS RE 2012 001 Left	60,000	Liow Ko	6
End Frame INS RE 2012 001 Right	60,000	Liow Ko	6
Entity Expert Alloy 90mm CHUN-E IRS-06 ϕ28.6	65,946	Garuda Enterprise	7
Entity Xpert Alloy 30.9x350mm Kalloy SP712N	65,946	Kalloy	7
Entity Xpert Alloy 680mm KY HB-RB12L Rise 15 ϕ31.8 Clamp Stem NDC	65,946	Leadtec	7
Eyelet 14G x 270	2,250,048	Chun Nan Jin Ji	23
Eyelet 14G x 272	2,250,048	Chun Nan Jin Ji	23
Front Brake Lever Shimano Acera BR-M395	70,314	Shimano Singapore	8
Front Shimano Alivio SL-M430 3 speed	43,964	Shimano Singapore	5
Handle Grip VLG1312AD2L Lock	71,892	Cheng's Enterprise	8
Hose Shimano Acera BR-M395	140,628	Shimano Singapore	15
KMC X-9 PGY 1/2x11/128x110 Links Super Light	43,964	KMC	5
Left Arm Shimano Acera FC-M391 170mm, 42x32x22T	46,876	Shimano Singapore	5
Left Arm Shimano Deore FC-M610	23,438	Shimano Singapore	3
Left Cup Shimano Hollowtech 2	23,438	Shimano Singapore	3
Lockring Shimano BB-UN26	46,876	Shimano Singapore	5
Nipple 14G x 270	2,250,048	Chun Nan Jin Ji	23
Nipple 14G x 272	2,250,048	Chun Nan Jin Ji	23
Outer Casing OT-40SP	240,000	Shimano Singapore	24
Promax 342Q 34.2QR	11,892	Ever Glory Machinery	2

Component	Purchased Quantity	Supplier	Order Quantity
Rear Brake Lever Shimano Acera BR-M395	70,314	Shimano Singapore	8
Rear Shimano Alivio SL-M430 9 speed	43,964	Shimano Singapore	5
Right Arm with Spindle Shimano Acera FC-M391 170mm, 42x32x22T	46,876	Shimano Singapore	5
Right Arm with Spindle Shimano Deore FC-M610	23,438	Shimano Singapore	3
Right Cup and Bearing Shimano Hollowtech 2	23,438	Shimano Singapore	3
Rim Tape Nylon Red 650B x 20mm	480,000	Cheng's Enterprise	24
Saddle	65,946	Overseas Technology	7
Saddle Steel Rail Velo Flux B XC	65,946	Overseas Technology	7
Schwalbe Smart Sam 27.5”x2.10”	480,000	Schwalbe Asia	24
Schwalbe SV 19	480,000	Schwalbe Asia	24
Seat Stay Bracket INS BR 2011	60,000	Liow Ko	6
Shimano Acera BL-M395	131,892	Shimano Singapore	14
Shimano Alivio FD-M430	43,964	Shimano Singapore	5
Shimano CS-HG20, 11-34T 9 Speed	43,964	Shimano Singapore	5
Shimano Deore CN-HG54, 1/2" x 11/128", Closing link: Chain Pin, 116 links	21,982	Shimano Singapore	3
Shimano Deore CS-HG62, 11-36T, 10 Speed	21,982	Shimano Singapore	3
Shimano Deore FD-M610	21,982	Shimano Singapore	3
Shimano Deore RD-M592SGS	43,964	Shimano Singapore	5
Shimano Deore RD-M610SGS	21,982	Shimano Singapore	3
Shimano Deore SL-M610 10 speed	21,982	Shimano Singapore	3
Shimano Deore SL-M610 3 speed	21,982	Shimano Singapore	3
Shimano FH-RM35 BL	65,946	Shimano Singapore	7
Shimano FH-RM35 BZBL	65,946	Shimano Singapore	7
Shimano SM-RT30 160 mm	131,892	Shimano Singapore	14
Side Kick Stand	65,946	Garuda Enterprise	7
Spoke 14G x 270	2,250,048	Chun Nan Jin Ji	23
Spoke 14G x 272	2,250,048	Chun Nan Jin Ji	23
SR Suntour XCM HLO Travel 100mm 1-1/8” Steerer	65,946	Suntour	7
Stem Cap SP 23 BK ϕf28.6	70,314	Leadtec	8
Sticker Insera Sena 5x4 cm	120,000	Label Jaya Pratama	12
Sticker SNI Poly M Cozmic CX 27.5	120,000	Duta Kalingga	12
VP Component VP-199	131,892	Ningbo	14
Washer 1SI110 28.6x33x10 mm	140,628	Garuda Enterprise	2
Washer 1SI110 28.6x33x5 mm	140,628	Garuda Enterprise	2

Appendix A26. Purchased Quantity and Order Quantity of Material for In-house Component of 27.5” Hard Tail Cross Country Sport MTB Family

Material	Raw Material Shape	Purchased Weight	Supplier	Order Quantity
Aluminium Alloy	Round Tubes	51,596.20	Taiyuan Kangmei	6
Aluminium Alloy	Square/ Rectangular Tubes	95,754.28	Taiyuan Kangmei	10

Appendix A27. Activity and Its Required Time for 100 mm Head Tube INS HT 2011 01

Component	Department	Activity	Required Time (min)
100 mm Head Tube INS HT 2011 01	Research and Development	Designing Part	60
	Inventory	Handling Raw Material from and to Inventory	10
		Handling Reworked Part from and to Inventory	10
		Receiving In-process Manufactured Component (Part / Sub Assembly) and Updating In-house Part Stock	5
		Receiving Raw Material and Updating Raw Material Stock	5
		Receiving Reworked Part and Updating Reworked Part Stock	5
		Handling In-house Part from and to Inventory	10
	Production Planning and Inventory Control	Designing Manufacturing Process	10
		Planning and Controlling Raw Material Inventory	5
	Quality Control	Determining In-house Part Quality Specification	5
		Determining Raw Material Quality Specification	5
		Determining Supplier Quality Specification for In-house Part	5
		Inspecting In-house Part	10
		Inspecting Incoming Raw Material	10
	Sourcing/Procurement	Evaluating Supplier Quality for In-house Component	1
		Procuring Raw Material	10
	Closed Die Forging	Preparing and Cleaning Manufacturing Equipment	10
		Receiving Supplies and Workpiece/Material	5
		Preparing Workpiece/Material and Tools	5
		Manufacturing Component	5
		Inspecting Manufacturing Process	1
		Post-processing Component	1
		Handling (Loading and Unloading) Manufactured Component	1
	Sawing	Preparing and Cleaning Manufacturing Equipment	10
		Receiving Supplies and Workpiece/Material	5
		Preparing Workpiece/Material and Tools	5
		Manufacturing Component	2
		Inspecting Manufacturing Process	1
		Post-processing Component	1
		Handling (Loading and Unloading) Manufactured Component	1
	Centre Type Grinding	Preparing and Cleaning Manufacturing Equipment	10
		Receiving Supplies and Workpiece/Material	5
		Preparing Workpiece/Material and Tools	5

Component	Department	Activity	Required Time (min)
		Manufacturing Component	5
		Inspecting Manufacturing Process	1
		Post-processing Component	1
		Handling (Loading and Unloading) Manufactured Component	1
	Solution Treating and Precipitation Hardening	Preparing and Cleaning Manufacturing Equipment	30
		Receiving Supplies and Workpiece/Material	5
		Preparing Workpiece/Material and Tools	5
		Manufacturing Component	2
		Inspecting Manufacturing Process	1
		Post-processing Component	1
		Handling (Loading and Unloading) Manufactured Component	1
	Polishing and Buffing	Preparing and Cleaning Manufacturing Equipment	10
		Receiving Supplies and Workpiece/Material	5
		Preparing Workpiece/Material and Tools	5
		Manufacturing Component	5
		Inspecting Manufacturing Process	1
		Post-processing Component	1
		Handling (Loading and Unloading) Manufactured Component	1
	Painting – Spray	Preparing and Cleaning Manufacturing Equipment	30
		Receiving Supplies and Workpiece/Material	5
		Preparing Workpiece/Material and Tools	5
		Manufacturing Component	15
		Inspecting Manufacturing Process	1
		Post-processing Component	1
		Handling (Loading and Unloading) Manufactured Component	1
	Alkaline Cleaning (Immersion and Spray)	Preparing and Cleaning Manufacturing Equipment	30
		Receiving Supplies and Workpiece/Material	5
		Preparing Workpiece/Material and Tools	5
		Cleaning Component	2
		Inspecting Manufacturing Process	1
		Post-processing Component	1
		Handling (Loading and Unloading) Manufactured Component	1

Appendix A28. Department and Its Resources for 100 mm Head Tube INS HT 2011 01

Department	Quantity Labour & Supervisor	Quantity Equipment	Quantity Supplies	Quantity Utilities	Quantity Facilities
Research and Development	10	30	1	1	1
Inventory	5	5	1	1	1
Production Planning and Inventory Control	10	10	1	1	1
Quality Control	25	75	1	2	1
Sourcing/Procurement	5	5	1	1	1
Closed Die Forging	50	150	1	2	1
Sawing	50	150	0	1	1
Centre Type Grinding	50	150	1	2	1
Solution Treating and Precipitation Hardening	15	30	0	2	1
Polishing and Buffing	50	100	0	1	1
Painting – Spray	25	25	1	2	1
Alkaline Cleaning (Immersion and Spray)	15	30	1	2	1

Appendix A29. Activity Driver and Activity Cost of 100 mm Head Tube INS HT 2011 01

Component	Department	Activity	Activity Driver	Cost ($)
100 mm Head Tube INS HT 2011 01	Research and Development	Designing Part	Constant=1	8.76
	Inventory	Handling Raw Material from and to Inventory	Quantity of Handlings for Raw Material	37.74
		Handling Reworked Part from and to Inventory	Quantity of Handlings for Reworked	2.70
		Receiving In-process Manufactured Component (Part / Sub Assembly) and Updating In-house Part Stock	Quantity of Production Runs	10.78
		Receiving Raw Material and Updating Raw Material Stock	Quantity of Purchased Material Orders	1.35
		Receiving Reworked Part and Updating Reworked Part Stock	Quantity of Production Runs	10.78
		Handling In-house Part from and to Inventory	Quantity of Handlings	26.96
	Production Planning and Inventory Control	Designing Manufacturing Process	Number of Manufacturing Process Types	10.18
		Planning and Controlling Raw Material Inventory	Quantity of Component Orders	1.45
	Quality Control	Determining In-house Part Quality Specification	Constant=1	1.45
		Determining Raw Material Quality Specification	Constant=1	1.45
		Determining Supplier Quality Specification for In-house Part	Number of Suppliers	18.86
		Inspecting In-house Part	Quantity of Inspections	1,740.60
		Inspecting Incoming Raw Material	Quantity of Inspections for Raw Material	29.01
		Inspecting Closed Die Forging Process	Quantity of Inspections for Manufacturing Process	1.68
		Inspecting Sawing Process	Quantity of Inspections for Manufacturing Process	0.87
		Inspecting Centre Type Grinding Process	Quantity of Inspections for Manufacturing Process	1.34
		Inspecting Solution Treating and Precipitation Hardening Process	Quantity of Inspections for Manufacturing Process	2.13
		Inspecting Polishing and Buffing Process	Quantity of Inspections for Manufacturing Process	0.87
		Inspecting Painting – Spray Process	Quantity of Inspections for Manufacturing Process	3.38
		Inspecting Alkaline Cleaning (Immersion and Spray) Process	Quantity of Inspections for Manufacturing Process	2.36
	Sourcing/Proc	Evaluating Supplier	Quantity of Supplier	22.00

Component	Department	Activity	Activity Driver	Cost ($)
	urement	Quality for In-house Component	Evaluations	
		Procuring Raw Material	Quantity of Purchased Material Orders	1.41
	Closed Die Forging	Preparing and Cleaning Manufacturing Equipment	Quantity of Production Runs	16.83
		Receiving Supplies and Workpiece/Material	Quantity of Production Runs	8.42
		Preparing Workpiece/Material and Tools	Quantity of Part Prototypes	21.04
			Quantity of Pre - Manufacturing Parts	21.04
			Production Volume of each In-house Component and Reworked Part	66,276
		Manufacturing Component	Quantity of Part Prototypes	21.04
			Quantity of Pre - Manufacturing Parts	21.04
			Production Volume of each In-house Component and Reworked Part	66,276
		Post-processing Component	Quantity of Part Prototypes	4.208
			Quantity of Pre - Manufacturing Parts	4.208
			Production Volume of each In-house Component and Reworked Part	13255.2
		Handling (Loading and Unloading) Manufactured Component	Quantity of Handlings for Part Prototype	0.2104
			Quantity of Handlings for Pre-Manufacturing Part	0.2104
			Quantity of Handlings for In-house Component and Reworked Part	2.3144
	Sawing	Preparing and Cleaning Manufacturing Equipment	Quantity of Production Runs	8.69
		Receiving Supplies and Workpiece/Material	Quantity of Production Runs	4.34
		Preparing Workpiece/Material and Tools	Quantity of Part Prototypes	10.86
			Quantity of Pre - Manufacturing Parts	10.86
			Production Volume of each In-house Component and Reworked Part	34209
		Manufacturing Component	Quantity of Part Prototypes	4.344
			Quantity of Pre - Manufacturing Parts	4.344
			Production Volume of each In-house Component and Reworked Part	13,683.6
		Post-processing Component	Quantity of Part Prototypes	2.172

Component	Department	Activity	Activity Driver	Cost ($)
			Quantity of Pre - Manufacturing Parts	2.172
			Production Volume of each In-house Component and Reworked Part	6841.8
		Handling (Loading and Unloading) Manufactured Component	Quantity of Handlings for Part Prototype	0.1086
			Quantity of Handlings for Pre-Manufacturing Part	0.1086
			Quantity of Handlings for In-house Component and Reworked Part	1.1946
	Centre Type Grinding	Preparing and Cleaning Manufacturing Equipment	Quantity of Production Runs	13.36
		Receiving Supplies and Workpiece/Material	Quantity of Production Runs	6.68
		Preparing Workpiece/Material and Tools	Quantity of Part Prototypes	16.7
			Quantity of Pre - Manufacturing Parts	16.7
			Production Volume of each In-house Component and Reworked Part	52,605
		Manufacturing Component	Quantity of Part Prototypes	16.7
			Quantity of Pre - Manufacturing Parts	16.7
			Production Volume of each In-house Component and Reworked Part	52,605
		Post-processing Component	Quantity of Part Prototypes	3.34
			Quantity of Pre - Manufacturing Parts	3.34
			Production Volume of each In-house Component and Reworked Part	10,521
		Handling (Loading and Unloading) Manufactured Component	Quantity of Handlings for Part Prototype	0.167
			Quantity of Handlings for Pre-Manufacturing Part	0.167
			Quantity of Handlings for In-house Component and Reworked Part	1.837
	Solution Treating and Precipitation Hardening	Preparing and Cleaning Manufacturing Equipment	Quantity of Production Runs	63.96
		Receiving Supplies and Workpiece/Material	Quantity of Production Runs	10.66
		Preparing Workpiece/Material and Tools	Quantity of Part Prototypes	26.65
			Quantity of Pre - Manufacturing Parts	26.65
			Production Volume of each In-house Component and Reworked Part	83,947.5
		Manufacturing	Quantity of Part	10.66

Component	Department	Activity	Activity Driver	Cost ($)
		Component	Prototypes	
			Quantity of Pre - Manufacturing Parts	10.66
			Production Volume of each In-house Component and Reworked Part	33,579
		Post-processing Component	Quantity of Part Prototypes	5.33
			Quantity of Pre - Manufacturing Parts	5.33
			Production Volume of each In-house Component and Reworked Part	16,789.5
		Handling (Loading and Unloading) Manufactured Component	Quantity of Handlings for Part Prototype	0.2665
			Quantity of Handlings for Pre-Manufacturing Part	0.2665
			Quantity of Handlings for In-house Component and Reworked Part	2.9315
	Polishing and Buffing	Preparing and Cleaning Manufacturing Equipment	Quantity of Production Runs	8.69
		Receiving Supplies and Workpiece/Material	Quantity of Production Runs	4.34
		Preparing Workpiece/Material and Tools	Quantity of Part Prototypes	10.86
			Quantity of Pre - Manufacturing Parts	10.86
			Production Volume of each In-house Component and Reworked Part	34,209
		Manufacturing Component	Quantity of Part Prototypes	10.86
			Quantity of Pre - Manufacturing Parts	10.86
			Production Volume of each In-house Component and Reworked Part	34,209
		Post-processing Component	Quantity of Part Prototypes	2.172
			Quantity of Pre - Manufacturing Parts	2.172
			Production Volume of each In-house Component and Reworked Part	6,841.8
		Handling (Loading and Unloading) Manufactured Component	Quantity of Handlings for Part Prototype	0.1086
			Quantity of Handlings for Pre-Manufacturing Part	0.1086
			Quantity of Handlings for In-house Component and Reworked Part	1.1946
	Painting – Spray	Preparing and Cleaning Manufacturing Equipment	Quantity of Production Runs	101.47
		Receiving Supplies and Workpiece/Material	Quantity of Production Runs	16.91

Component	Department	Activity	Activity Driver	Cost ($)
		Preparing Workpiece/Material and Tools	Quantity of Part Prototypes	42.28
			Quantity of Pre - Manufacturing Parts	42.28
			Production Volume of each In-house Component and Reworked Part	133,182
		Manufacturing Component	Quantity of Part Prototypes	126.84
			Quantity of Pre - Manufacturing Parts	126.84
			Production Volume of each In-house Component and Reworked Part	399,546
		Post-processing Component	Quantity of Part Prototypes	8.456
			Quantity of Pre - Manufacturing Parts	8.456
			Production Volume of each In-house Component and Reworked Part	26,636.4
		Handling (Loading and Unloading) Manufactured Component	Quantity of Handlings for Part Prototype	0.4228
			Quantity of Handlings for Pre-Manufacturing Part	0.4228
			Quantity of Handlings for In-house Component and Reworked Part	4.6508
	Alkaline Cleaning (Immersion and Spray)	Preparing and Cleaning Manufacturing Equipment	Quantity of Production Runs	70.90
		Receiving Supplies and Workpiece/Material	Quantity of Production Runs	11.82
		Preparing Workpiece/Material and Tools	Quantity of Part Prototypes	29.54
			Quantity of Pre - Manufacturing Parts	29.54
			Production Volume of each In-house Component and Reworked Part	93,051
		Cleaning Component	Quantity of Part Prototypes	11.816
			Quantity of Pre - Manufacturing Parts	11.816
			Production Volume of each In-house Component and Reworked Part	37,220.4
		Post-processing Component	Quantity of Part Prototypes	5.908
			Quantity of Pre - Manufacturing Parts	5.908
			Production Volume of each In-house Component and Reworked Part	18,610.2
		Handling (Loading and Unloading) Manufactured Component	Quantity of Handlings for Part Prototype	0.2954
			Quantity of Handlings for Pre-Manufacturing Part	0.2954

Component	Department	Activity	Activity Driver	Cost ($)
			Quantity of Handlings for In-house Component and Reworked Part	3.2494

Appendix A30. Component Rate of 100 mm Head Tube INS HT 2011 01

Component	Recovered Material Cost ($/unit)	Raw Material Cost ($/unit)	Material Storage Cost ($/unit)	Component Storage Cost ($/unit)	Activity Cost ($/unit)	Outsourced Component Cost ($/unit)	Component Rate ($/unit)
100 mm Head Tube INS HT 2011 01	0	0.324	0.001	0.006	20.63	0	20.961

Appendix A31. Product Platform Rate of 27.5“ Hard Tail XC MTB size 16

Product Platform	Total Recovered Sub Module Cost ($/unit)	Total Sub Module Cost ($/unit)	Sub Module Storage Cost ($/unit)	Product Platform Storage Cost ($/unit)	Product Platform General Activity Cost ($/unit)	Product Platform Assembling Activity Cost ($/unit)	Product Platform Rate ($/unit)
27.5“ Hard Tail XC MTB size 16	36.947	394.167	3.530	3.530	0.076	35.070	473.320

Appendix A32. Product Variant Rate of Cozmix CX1.0 27.5 size 16

Product Variant	Total Recovered Sub Module Cost of Variant ($/unit)	Total Sub Module Cost of Variant ($/unit)	Sub Module Storage Cost of Variant ($/unit)	Variant Storage Cost ($/unit)	Taken Back Product General Activity Cost ($/unit)	Taken Back Product Disassembling Activity Cost ($/unit)	Taken Back Product Storage Cost ($/unit)
Cozmix CX1.0 27.5 size 16	2.359	76.041	0.625	0.625	0.612	0.656	0.656

Product Variant General Activity Cost ($/unit)	Variant Assembling Activity Cost ($/unit)	Product Platform Rate ($/unit)	Product Variant Rate ($/unit)
5.790	6.985	473.320	567.670

Appendix A33. Cost of each Category of 100 mm Head Tube INS HT 2011 01

Component	Cost Category	Cost ($/unit)
100 mm Head Tube INS HT 2011 01	Product Development Cost	0
	Product Design Cost	0.000223315
	Product Evaluation Cost	0
	Production Planning Cost	0.000261223
	Inventory Control Cost	0.000419994
	Procurement Cost	0.006842424
	Manufacturing Cost	20.55538476
	Assembly Cost	0
	Packaging Cost	0
	Quality Control Cost	0.06462897
	Inventory Cost	0.009401876
	Marketing Cost	0
	Sales Cost	0
	Transportation Cost	0
	Customer Service Cost	0
	Warranty Cost	0
	Take Back Cost	0
	End of Life Cost	0
	Disassembly Cost	0
	Material and Component Cost	0.32374656

Appendix A34. Cost of each Category of 27.5“ Hard Tail XC MTB size 16

Product Platform	Cost Category	Cost ($/unit)
27.5“ Hard Tail XC MTB size 16	Product Development Cost	0
	Product Design Cost	0
	Product Evaluation Cost	0
	Production Planning Cost	0.0001454
	Inventory Control Cost	0
	Procurement Cost	0.002538
	Manufacturing Cost	70.27184126
	Assembly Cost	35.07040469
	Packaging Cost	0
	Quality Control Cost	0.0436117
	Inventory Cost	7.088761826
	Marketing Cost	0
	Sales Cost	0
	Transportation Cost	0
	Customer Service Cost	0
	Warranty Cost	0
	Take Back Cost	0
	End of Life Cost	36.94712344
	Disassembly Cost	0
	Material and Component Cost	323.8954278

Appendix A35. Cost of each Category of Cozmix CX1.0 27.5 size 16

Product Variant	Cost Category	Cost ($/unit)
Cozmix CX1.0 27.5 size 16	Product Development Cost	0.000219
	Product Design Cost	0.000438
	Product Evaluation Cost	0.001825
	Production Planning Cost	0.0007997
	Inventory Control Cost	0.0004362
	Procurement Cost	0.003948
	Manufacturing Cost	70.27184126
	Assembly Cost	42.05585742
	Packaging Cost	4.659525
	Quality Control Cost	0.131765838
	Inventory Cost	9.052734772
	Marketing Cost	0.72776025
	Sales Cost	0.060469875
	Transportation Cost	0.11961625
	Customer Service Cost	0.02254505
	Warranty Cost	0.07269605
	Take Back Cost	0.6150285
	End of Life Cost	2.359335795
	Disassembly Cost	0.65599875
	Material and Component Cost	399.9360009

Appendix A36. Life Cycle Cost of 100 mm Head Tube INS HT 2011 01

Component	Life Cycle Stage	Life Cycle Cost ($/unit)
100 mm Head Tube INS HT 2011 01	Research and Development Stage	0.000223315
	Production Stage	20.960685812
	After Sales Stage	0
	End of Life Stage	0

Appendix A37. Life Cycle Cost of 27.5“ Hard Tail XC MTB size 16

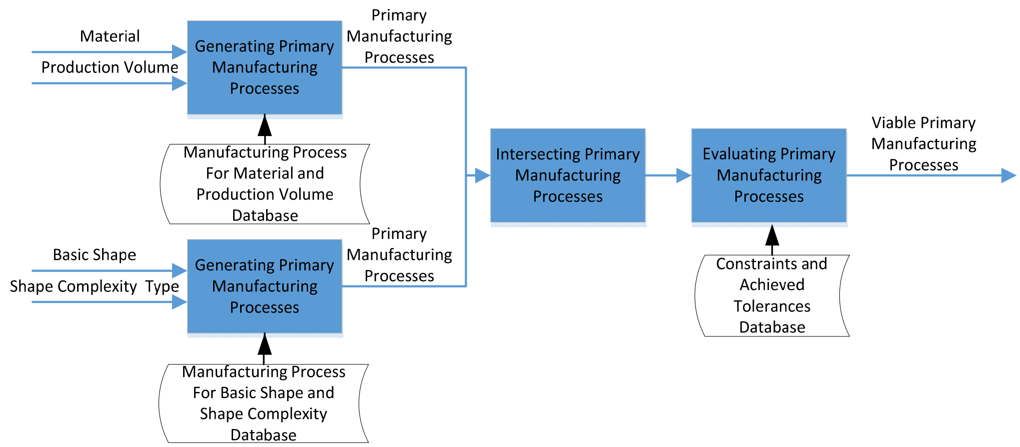
Product Platform	Life Cycle Stage	Life Cycle Cost ($/min)
27.5“ Hard Tail XC MTB size 16	Research and Development Stage	0
	Production Stage	436.373
	After Sales Stage	0
	End of Life Stage	36.947

Appendix A38. Life Cycle Cost of Cozmix CX1.0 27.5 size 16

Product Variant	Life Cycle Stage	Life Cycle Cost ($/min)
Cozmix CX1.0 27.5 size 16	Research and Development Stage	0.002
	Production Stage	527.021
	After Sales Stage	0.095
	End of Life Stage	3.630

Appendix B: Guideline for Manufacturing Process Chain Generation

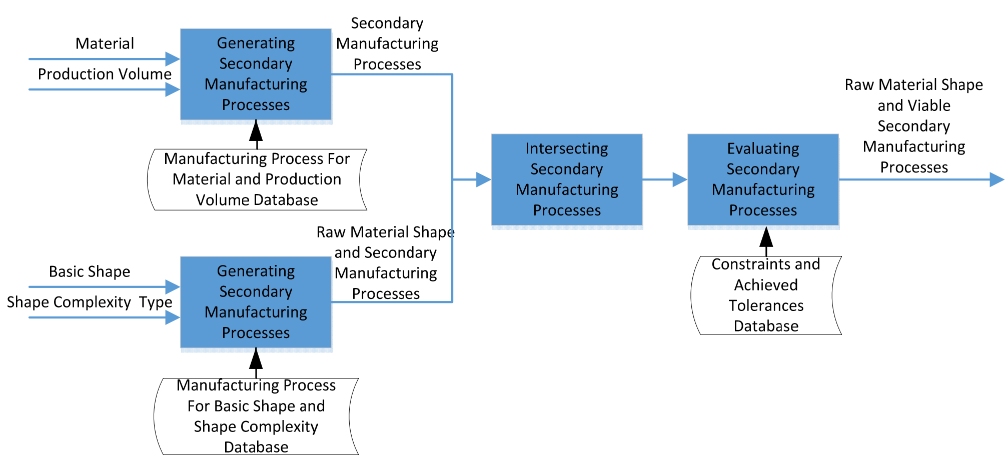
1. Generate all primary processes that can be used to form the required main shape of a component with its material, envelope size, and minimum thickness in the required amount of production volume.



List all primary processes that are economically viable to manufacture a component material in a certain amount of production volume

   a. List all primary processes that can form the main shape (basic shape and complexity) of a component
   b. List the overlap of the two primary processes lists above
   c. Remove all primary processes that cannot manufacture the size/weight or the thickness

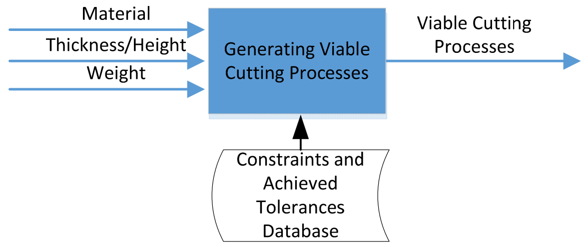
2. Generate all secondary processes that can be used to modify the common shape of raw material into the required main shape of a component with its material, envelope size, and minimum thickness in the required amount of production volume.



   a. List all secondary processes that are economically viable to manufacture the component material in a certain amount of production volume
   b. List all secondary processes that can form the main shape (basic shape and complexity) of the component from the common shape of raw material
   c. List the overlap of the two secondary processes lists above

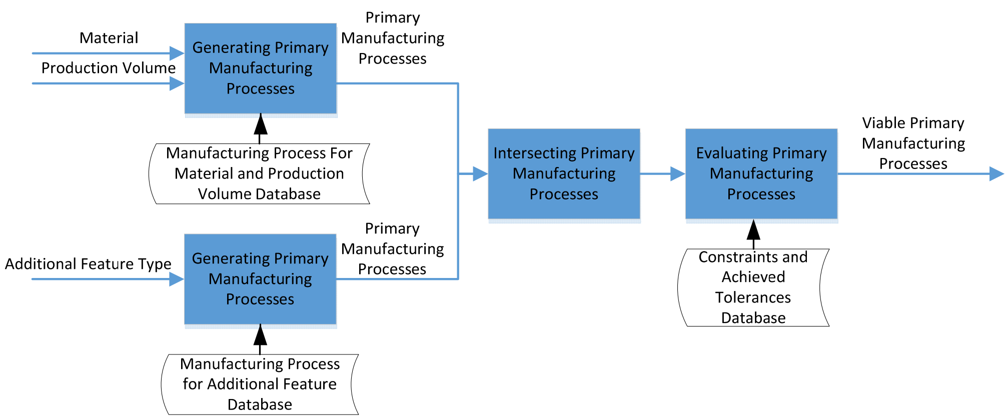
d. Remove all secondary processes that cannot manufacture the size/weight or the thickness

3. Combine all feasible primary and secondary processes that can be used to form the required main shape and to modify the common shape of raw material into the required main shape of a component, and then select the best process.
4. (If the best manufacturing process is categorised as the secondary manufacturing process) Generate and select cutting out process that can be used to cut the common shape of raw material into the required size of a component suitable with its material and envelop size in the required amount of production volume.



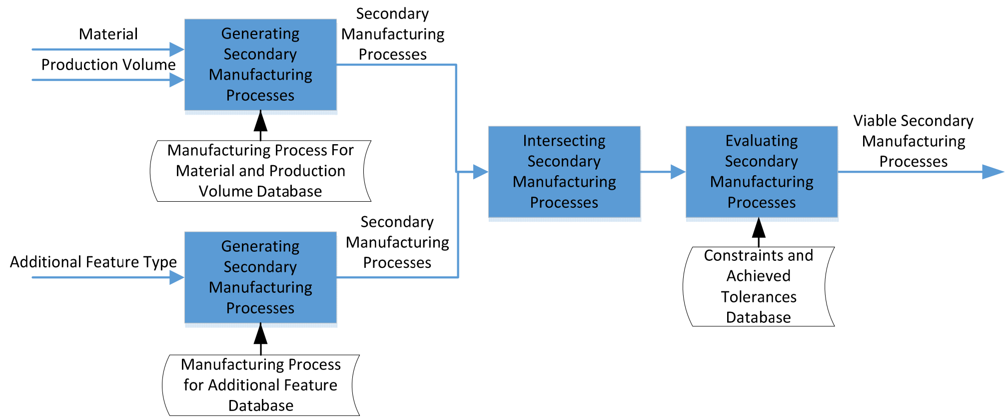
a. List all cutting out processes that can cut the material, size, and weight
b. Select one cutting out process to cut the common shape of raw material into the required size of a component

5. Generate all primary processes that can be used to add the additional features to the already shaped component.



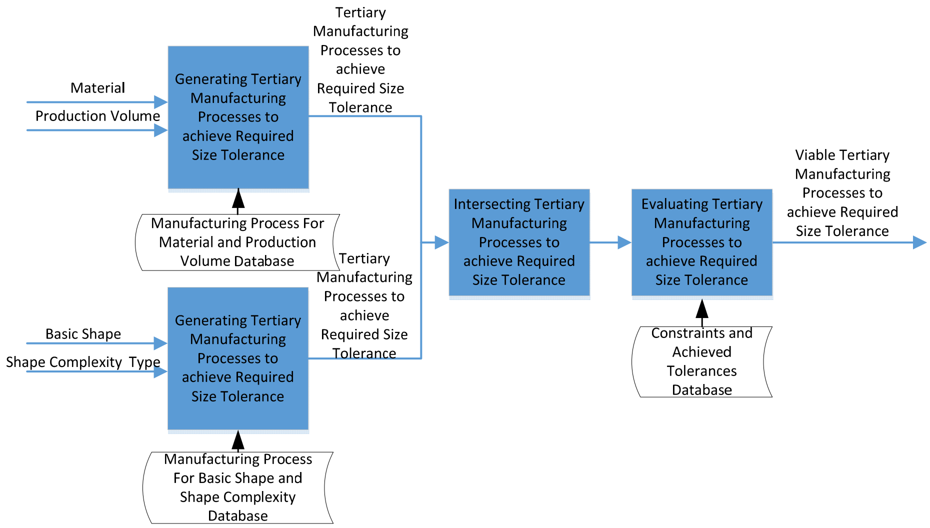
a. List all primary processes that are economically viable to manufacture a component material in a certain amount of production volume
b. List all primary processes that can add each additive feature and each subtractive feature
c. List the overlap of the two secondary processes lists above
d. Remove all primary processes that cannot manufacture the size/weight or the thickness

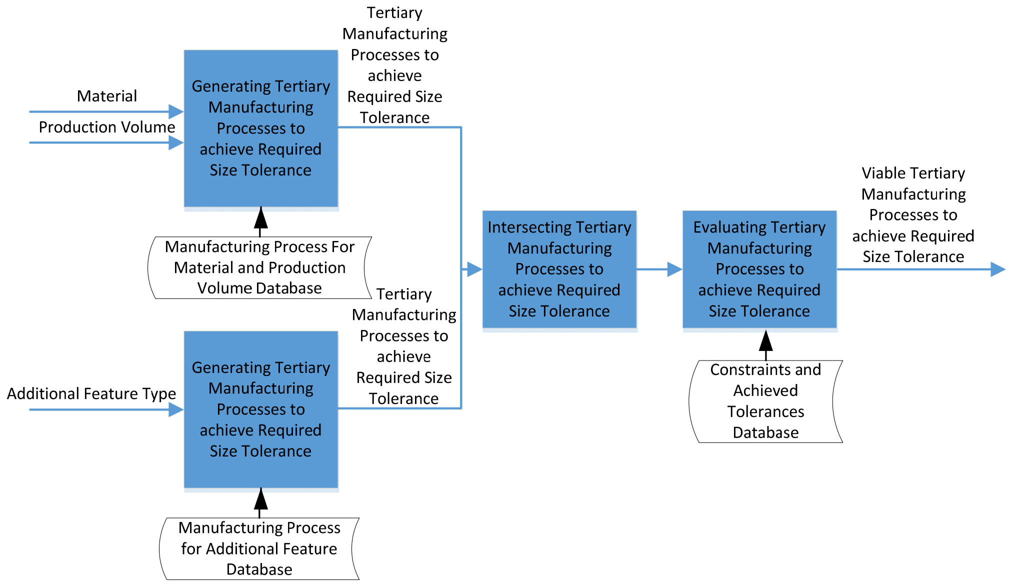
6. Generate all secondary processes that can be used to add the additional features to the already shaped component.



   a. List all secondary processes that are economically viable to manufacture the component material in a certain amount of production volume
   b. List all secondary processes that can add each additive feature and each subtractive feature
   c. List the overlap of the two secondary processes lists above
   d. Remove all secondary processes that cannot manufacture the size/weight or the thickness

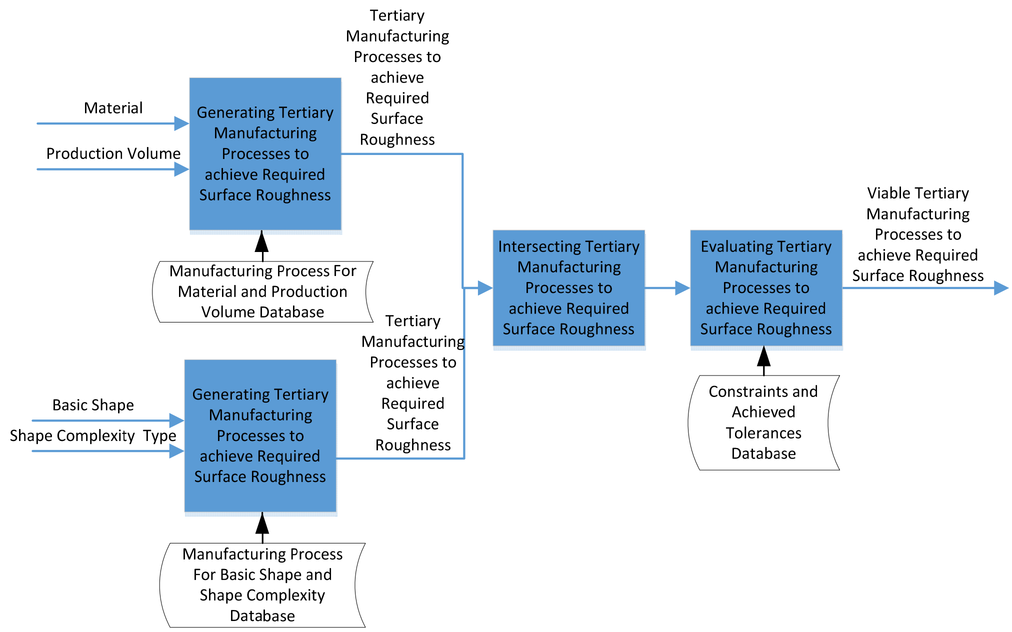
7. Combine all feasible primary and secondary processes that can be used to add the additional features and then select the best feasible process
   - If the best process for the main shape is categorised as the secondary manufacturing process then the feasible processes for the additional feature is only the secondary process category.
   - If the best process for the main shape is categorised as the primary manufacturing process then
     a. the primary feasible processes for the additional feature is only the intersect between primary manufacturing process for the main shape and for the additional feature.
     b. the secondary feasible process for the additional feature is all the feasible secondary processes.
8. Generate and select tertiary process that can be used to achieve the required size tolerance of the already shaped component without affecting the shape and the features geometry of the component for each chain

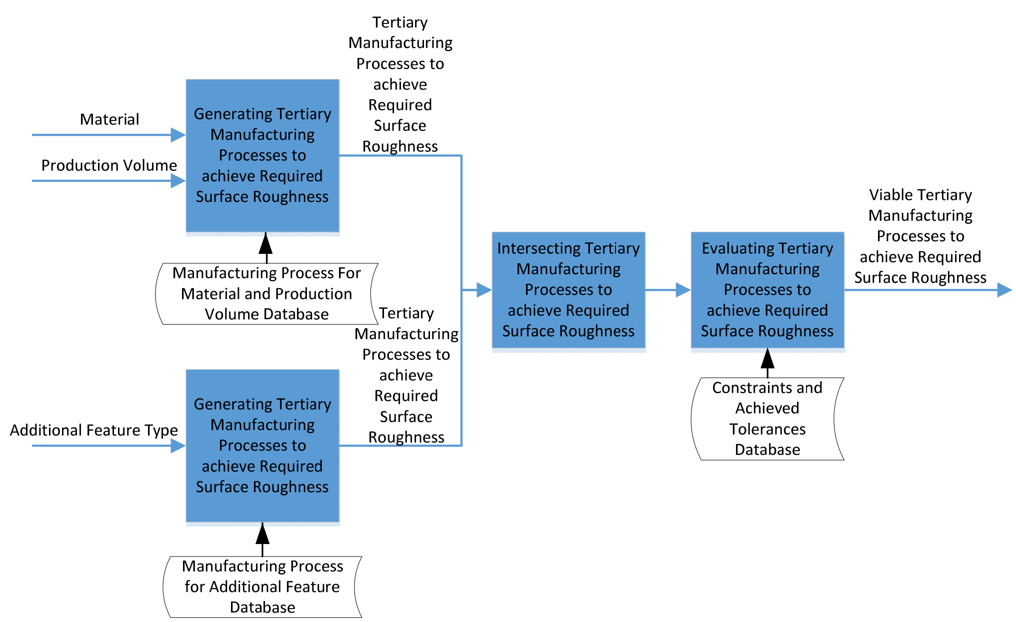




a. Compare the achieved size tolerance to the required size tolerance of the main shape and the additional features for each chain. If the required size tolerance is achieved, no tertiary process with stock removal is required.
b. If the required size tolerance is not achieved then list the tertiary process with stock removal that suitable can be used to achieve the required size tolerance of the already shaped component for each chain
    i. List all tertiary processes with stock removal that are economically viable to manufacture a component material in a certain amount of production volume
    ii. List the tertiary process with stock removal that suitable for the main shape and/or the additional features
    iii. List the overlap of the two tertiary processes lists above
    iv. Remove all tertiary processes that cannot manufacture the size/weight
    v. Select one tertiary process with stock removal from the overlap for each chain

9. Generate and select tertiary process that can be used to achieve the surface roughness of the already shaped component without affecting the shape and the features geometry of the component for each chain

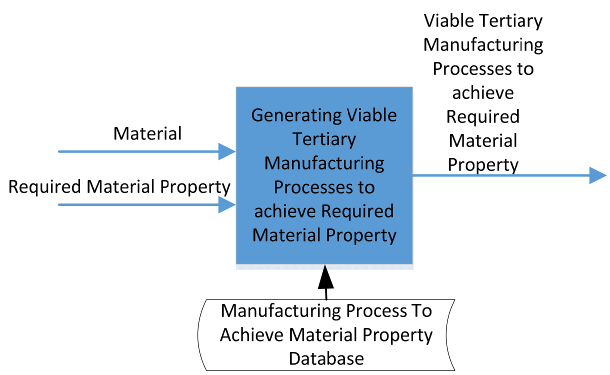




a. Compare the achieved surface roughness to the required surface roughness of the main shape and the additional features for each chain. If the required surface roughness is achieved, no tertiary process without stock removal is required.
b. If the required surface roughness is still not achieved then list the tertiary process without stock removal that can be used to achieve the surface roughness of the already shaped component for each chain

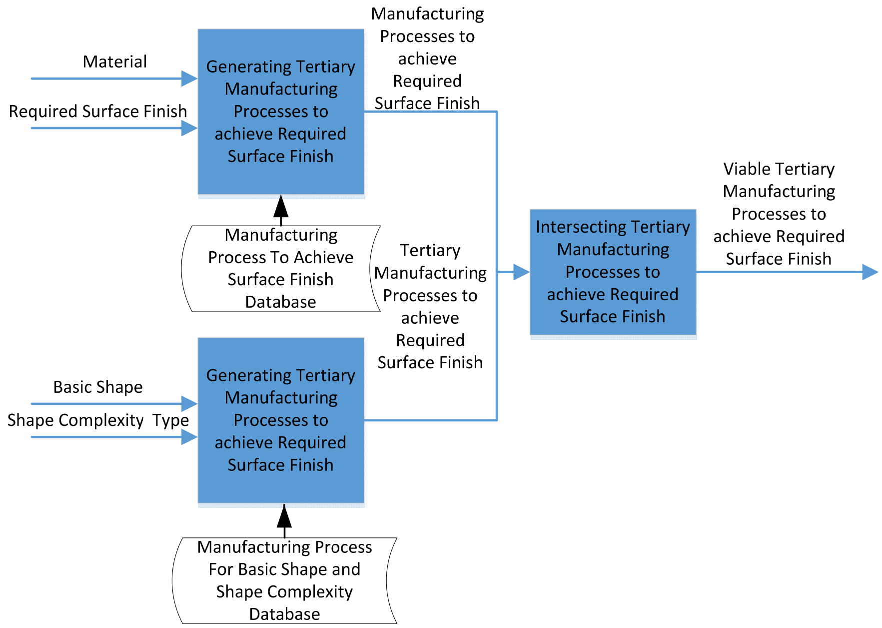
i. List all tertiary processes that are economically viable to manufacture a component material in a certain amount of production volume
ii. List the tertiary process to achieve the surface roughness that suitable for the main shape and/or the additional feature
iii. List the overlap of the two tertiary processes lists above
iv. Remove all tertiary processes that cannot manufacture the size/weight
v. Select one tertiary process to achieve the surface roughness from the overlap for each chain

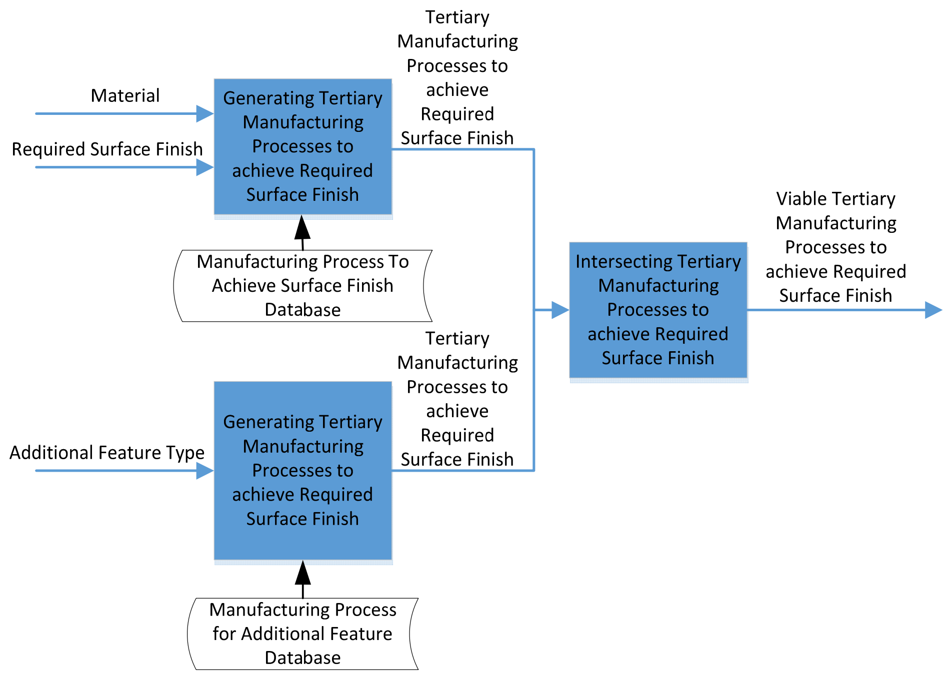
10. Generate and select the tertiary process that can be used to harden, soften, or strengthen the material of the already shaped component for each chain



a. If it is required to harden, soften, or strengthen the material of the already shaped component, then list the tertiary process that suitable to achieve the required properties of the material for each chain
b. Select one tertiary process to harden, soften, or strengthen the material of the already shaped component for each chain

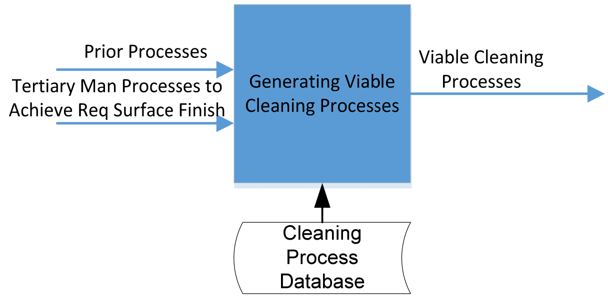
11. Generate and select tertiary process that can be used to improve the surface finish of the already shaped component without affecting the shape, the features geometry, the surface requirements, and the material properties of the component for each chain





a. If it is required to improve the surface finish of the already shaped component, then list the tertiary processes that can be used to improve the surface finish of the component for each chain
b. List the tertiary process to improve the surface finish that suitable for the main shape and/or the additional feature
c. List the overlap of the two tertiary processes lists above
d. Select one tertiary process to improve the surface finish of the already shaped component for each chain

12. Generate tertiary process to clean the component for each chain



   a. List the tertiary processes that can be used to clean the component that suitable for prior and post processes for each chain
   b. Select one tertiary process to clean the component for each chain

13. Generate the viable manufacturing process chains and the required cleaning process
   a. Add of best primary or secondary manufacturing process for the main shape
   b. Add the selected cutting process
   c. Add of best primary or secondary manufacturing process for the additional feature
   d. Add the selected tertiary process to achieve the size tolerance of the already shaped component for each chain
   e. Add the selected tertiary process to achieve the surface roughness of the already shaped component for each chain
   f. Add the selected tertiary process that suitable to harden, soften, or strengthen the material for each chain
   g. Add the selected cleaning process to clean the component before conducting the surface finish process
   h. Add the selected tertiary process to improve the surface finish of the component for each chain